SENSORS AND DATA SYSTEMS 6

Useful Applications of Earth-Oriented Satellites

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Prepared by Panel 6 of the
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PREFACE

In the fall of 1966, the National Aeronautics and Space Administration (NASA) asked the National Academy of Sciences to conduct a study on "the probable future usefulness of satellites in practical Earth-oriented applications." The study would obtain the recommendations of highly qualified scientists and engineers on the nature and scope of the research and development program needed to provide the technology required to exploit these applications. NASA subsequently asked that the study include a consideration of economic factors.

Designated "The Summer Study on Space Applications," work began in January 1967, guided by a Central Review Committee (CRC) appointed by the Academy. The Study's Chairman was Dr. W. Deming Lewis, President of Lehigh University.

Technical panels were convened to study practical space applications and worked intensively for periods of two to three weeks during the summers of 1967 and 1968 at Little Harbor Farm in Woods Hole, Massachusetts. The work of each panel was then reported to the Central Review Committee, which produced an overall report. Panels were convened in the following fields:

Panel 1: Forestry-Agriculture-Geography

Panel 2: Geology

Panel 3: Hydrology

Panel 4: Meteorology

Panel 5: Oceanography

Panel 6: Sensors and Data Systems

Panel 7: Points-to-Point Communications

Panel 8: Systems for Remote-Sensing Information and Distribution

Panel 9: Point-to-Point Communications

Panel 10: Broadcasting

Panel 11: Navigation and Traffic Control

Panel 12: Economic Analysis

Panel 13: Geodesy and Cartography

The assigned function of the Panel on Sensors and Data Systems was to assess the state of the art and to provide technical information to the various other panels of the Study on the hardware (and software) portions of an earth-observation system. The competence of this Panel was necessarily broad and diverse and had emphasis in the sensors area.

Individual members of the Panel on Sensors and Data Systems worked closely with the disciplinary groups in formulating system concepts, appraising capabilities, and specifying sensor requirements. The main output of this Panel is, therefore, incorporated in the reports of the other panels. In addition, members of the Sensors Panel prepared a series of papers, largely tutorial in nature, that provide background material and some expansion of the concepts incorporated in the various reports. These papers have been assembled in this volume for ready reference.

It seems clear at this point that multisensor and, in particular, multispectral imaging sensor systems will form the backbone of future earth-observation systems and will provide the greatest information return per dollar invested. The capability for identification of scene elements is increased many times when data are available in several portions of the spectrum, as compared with a single portion. In many cases, suitable multiband systems for spacecraft (and even for aircraft in many cases) have not yet been designed. This development should be given priority status.

The advent of multisensor systems tends to aggravate an already troublesome data-rate and data-handling situation. Therefore, new and emerging methods for handling large quantities of multiband data, particularly data in image form, require immediate additional attention. A critical need is the development of new techniques for the storage of massive amounts of quantitative data, especially on-board data.

It is important at this time to pursue the development of the interface between the output of the data-analysis algorithms and the consumer's use of the resulting information. It is generally possible now to generate more information than can be assimilated into the socioeconomic system, chiefly because the socioeconomic system has hitherto been unaware of space systems as sources of information. The reports of the other panels are expected to point the way in this regard.

The first-generation systems recommended by most of the discipline-oriented panels are intended to produce photographic prints of the sensor outputs. In view of the need for interface development between the information supplier and the consumer, this seems to be a suitably conservative but particularly appropriate approach. Since information consumers are already knowledgeable of this data format, early economic benefits may be expected. Meanwhile, experience valuable in implementing the more ambitious second-generation systems is gained.

The second-generation systems proposed are generally more sophisticated, relying more heavily on analytical techniques for extracting the ultimate information from data. This seems justified at this point, although a considerable research effort will be necessary to develop such analysis techniques. The channels for information dissemination established for first-generation systems can serve the additional function of helping to build user confidence in these new algorithms.

The Panel on Sensors and Data Systems compiled an interim report during the summer of 1967 under the chairmanship of Dr. David A. Landgrebe. This report was revised during the summer of 1968 under Dr. Landgrebe's leadership.

The major part of the Study was accomplished by the panels; the function of CRC was to review their work, to evaluate their findings, and, in the context of the total national picture, to derive certain conclusions and

and recommendations, which have been presented in Useful Applications of Earth-Oriented Satellites: Report of the Central Review Committee.

In concluding this preface, it is emphasized that the conclusions and recommendations of this panel report should be considered within the context of the overall report of the Central Review Committee.

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APPENDIXES

1.0 INTRODUCTION

1.1 Rationale of Multisensor Analysis

All objects have attributes that allow them to be identified upon detailed inspection. In many situations, objects can be identified remotely by electromagnetic sensing. Such identification processes range in complexity from casual visual observations to spectrochemical analysis. The key to developing an optimum remote sensor is one of determining how detailed an inspection is required to do the desired identification within acceptable error limits and which properties of the material must be used for rapid identification. The attributes that can be sensed remotely by electromagnetic radiation are spatial distribution (shape and texture), spectral distribution (color), polarization, temporal variations, and variation of the above factors with angle of observation. These remotely sensed parameters together with other factors such as geographical location, season, and meteorological condition can be combined to identify an object under observation. Clearly the more bits of pertinent information that one can factor into the sensing system, i.e., number of parameters, observation accuracy, and degree of fineness (spatial and spectral resolution), the more reliable the identification.

When observing large areas at fine spatial resolutions, the data rate and volume become intolerable. Imagery of the United States at 2-ft ground resolution would require 2560 lb of film for storage and return by data capsule or 121 days of continuous telemetry on a 10-M data link. Thus identification based on shape information from spaceborne sensors, unless preceded by on-board data reduction, must be limited to large features or use of statistical sampling of smaller areas. Vegetation cannot, it seems, be identified on the basis of shape information. Rather than rely entirely on spatial information, it is probable that the optimum sensor will sense spectral and spatial information simultaneously. At best, the spectral information will permit identification of selected features; at worst, spectral information can be used to enhance the contrast between features being sought and their background.

The problem of identifying an object on the basis of observable characteristics and other factors known at the time of observation is one of pattern recognition. The spectral characteristics of a scenepoint are observed, and a decision must be made whether a given subject matter occupies the scenepoint. This decision can be computed from the remotely sensed measurements, provided the probability distribution functions (signatures) of the object and likely backgrounds are known. This computing may be done by a human who can, for example, recognize an object on the basis of shape and color, or it may be done by electronic or electro-optical techniques. Data-processing techniques are described in Section 3.

Classification on the basis of spectral information has many levels of sophistication ranging from broad land-use classification to soil and mineral identification. The amount of spectral data needed for classification depends upon the spectral properties of the object being sought, the spectral properties of the background objects, and the acceptable error rate. For some tasks such as cloud/terrain or water/land identification, a single spectral band may be satisfactory.

The discrimination by multiband sensing is enormous. Assume that in a given spectral region a sensor can observe 10 gray levels. Only 10 states can exist in such a sensor. If the signals observed by visible, infrared, and radar sensors are mutually exclusive, then 10^3 states exist in this three-channel system. As will be discussed in Section 2, the optical spectrum alone can be split into more than 40 bands with sufficient signal-to-noise ratio to permit scanning of the scene and recognition of small differences in emission and/or reflectance. The problem is not one of instrumentation technology, but one of determining whether objects of interest have sufficiently different spectral properties to permit reliable detection with acceptable error rates. This statistical information can only be obtained by measurement and observation.

It is, of course, in understanding just how the properties of objects affect the sensed radiation that object signatures can be obtained. However, any variations in the sensed radiation, whether caused by variations in the properties of the source, of the atmospheric transmission path, of the object, or of the sensor, are noise in the system if they cannot be measured (or predicted) and taken into account. For example, the emittance and reflectance of an object in the field vary with the surface conditions of the object. In general, the way in which these properties vary can be measured, but these variations cannot be accounted for if one does not know the surface conditions at the time of the observation.

On the other hand, variations in the temperature of an object with the time of day or season can be both measured and taken into account. It is quite obvious, then, that the properties of an object which give rise to target signatures must be studied to determine how they vary parametrically with wavelength, aspect angles, and polarization, for example, so that it may be ascertained which of these properties are least sensitive to parameters that cannot be controlled during the remote-sensing measurement.

1.2 Spectral Characteristics of Terrestrial Features

There are several broad areas of the spectrum where different properties of the material can be studied. In the region between 0.32-4.0μ one observes primarily the spectral reflectance of direct and scattered solar radiation. Spectral variations arise from selective absorption (e.g., by chlorophyll, pigments, and liquid water) and differential scattering. In the 4.5-15μ region one observes thermal emission largely originating at the surface of solids and liquids. This emission is roughly proportional to the fifth power of its surface temperature in this spectral region, in accordance with Planck's blackbody law. The emission is also proportional to the emissivity which is here quite high (>0.9) for most naturally occurring surfaces. Minerals are often characterized by narrow "reststrahlen" regions, in which the emissivity is anomalous also.

In the microwave region 1-300 mm, one again observes thermal emission, which is here proportional to the product of the temperature and emissivity. The emissivities of most natural surfaces are smaller in this region than at shorter wavelengths; they also vary more widely from one suface to the next, so that passive microwave images are strongly influenced by emissivity variations. The emissivity, in turn, is a function of the permittivity; depending on the dielectric properties of the material, the radiant temperature at microwave frequencies may be an internal (subsurface) one. The microwave emissivity also depends, to a lesser extent, on the geometrical configuration of the surface under observation. Indeed, an important difference between the passive microwave and radar techniques, operating at the same wavelength, is that surface geometry effects dominate radar back-scatter signals, but play a smaller role in passive microwave emission signals.

Radar operates in wavelengths of the order of centimeters to meters, although future systems may operate at shorter wavelengths, using laser sources. Radar provides its own illumination and observes the scattered signal.

The scattered signal in the microwave region is influenced by the shape of the scatterer and its dielectric permittivity and is a function of the incident angle. At angles well away from the vertical, rough surfaces back-scatter more than smooth surfaces, and consequently rough surfaces are brighter on a radar image than smooth surfaces of similar dielectric properties. The permittivity is strongly influenced by moisture content on natural surfaces; i.e., plants with high moisture content are much better scatterers than dry plants with the same geometry.

Although the permittivity is a function of wavelength, resonant effects due to differing relative size, in wavelengths, of different parts of natural surfaces are probably more responsible for the spectral variations of radar scatter. Radar signals penetrate through plants and soil to some extent, with the shorter wavelengths penetrating shorter distances; thus the scattering sources are not only on the first surface intercepted by the wave, but rather may be up to several meters deep for long wavelengths in dry areas --and almost always the source involves depths of at least centimeters. This is a significant distinction between the microwave and other regions of the spectrum.

1.3 Atmospheric Effects

By far the biggest unknown factor in making quantitative radiometric and reflectance measurements in the optical spectral region of the earth's surface from a spacecraft is the attenuation--scattering and emission by the intervening atmosphere. In the 0.32-4μ region during daylight the magnitude of solar irradiation of the earth is modified by absorption and scattering. By and large the effects of absorption can be minimized by operating in the atmospheric windows, and the residual absorption effects can be computed. Scattering, however, is a variable ranging from light molecular scattering to opaque clouds. If the scattering is uniform over an area containing two known objects, the effects of scattering can be measured if surfaces of known reflectance are present in the field of view, and if the sensor has adequate signal-to-noise ratio and sufficient dynamic range.

In the thermal emission region, attenuation and emission by scattering particles in the atmosphere can lead to serious errors in quantitative observations unless accounted for. The scattering medium absorbs a fraction of the object's radiation and replaces it with a generally smaller fraction, since the temperature of atmospheric scattering particles is normally cooler than an object at the surface of the earth. As in the reflected-radiation case, correction for scattering by the intervening atmosphere is quite difficult. It can be made from remotely sensed data only if the scattering is uniform over a large area containing two known objects of different temperature or emissivity.

In the microwave region, waves longer than about 2 cm penetrate the clear atmosphere with no attenuation. At 1.35 cm a water-vapor absorption band introduces significant attenuation. The only other atmospheric attenuation of note in this wavelength region is the oxygen line at 6-mm wavelength.

Clouds introduce attenuation proportional to the fourth power of frequency, with about 1 dB/km for 1 cm wavelength and 1 g/m^3 moisture content. Thus, at 3 cm, even for a 10 g/m^3 cloud the attenuation does not exceed about 1 dB/km. Since spaceborne sensors look nearly straight down through the clouds, the total path is small, and radar is essentially unaffected by clouds for wavelengths longer than 3 cm and seldom affected for wavelengths on either side of the 1.35-cm absorption line.

Precipitation introduces more attenuation than clouds when the drops are large. For 1 cm this may get as high as 10 dB/km for a rainfall rate of 100 mm/hr. At 3 cm this may be as high as about 2 dB/km. Thus, for the rare cases when rain is that heavy, longer-wavelength systems are required to penetrate the rain.

Precipitation echoes may also be a problem for radars, but they can be discriminated by the Doppler processing inherent in synthetic-aperture systems; and reception of a cross-polarized component essentially eliminates precipitation echo but at some sacrifice in signal received. Experience with synthetic-aperture systems indicates that precipitation echoes will not be significant for this type of system at 3 cm and longer wavelengths. More research is needed to define this boundary. The use of radars operating at wavelengths of 3 cm and longer with synthetic-aperture techniques will be essentially unaffected by precipitation and clouds.

2.0 SENSOR TECHNIQUES

2.1 Optical—Mechanical Line Scanning in the 0.3-15μ Region

Section 1 discussed the discrimination potential of a sensor that uses the spectral information content in a scene. Ideally one would like a sensor system that operates in all regions of the electromagnetic spectrum. In the atmospheric windows one observes the spectral radiance or reflectance of the earth; in the absorption bands one observes the atmosphere. Because of sensor limitations and the different scan techniques and formats it is not presently possible to observe simultaneously a given resolution element of a scene at all wavelengths. Instead, hard copy imagery is made of each spectral band and then intercompared. (An exception is color photography.) Approaches to the tasks of analyzing and extracting spectral information from multisensor imagery are discussed in Section 3.

It is possible to obtain simultaneous multispectral data in the entire optical spectral region by slight modification of the optical-mechanical scanner [4]. An optical-mechanical scanner is merely a radiometer whose narrow field of view is systematically scanned over the scene by moving optical components. When used as an airborne infrared stripmapper, a rotating mirror scans the field of view lateral to the aircraft direction and the forward motion provides the other direction of scan [4]. Another variation of the optical-mechanical scanner is the ATS spin camera [11]. This framing camera is mounted in a spin-stabilized satellite in synchronous orbit, and scanning in one direction is performed by the rotation of the satellite and in the other direction by nodding the radiometer. For earth-surface observations, practical operation is limited to atmospheric windows between 0.32 and 15μ. For atmospheric soundings, the absorption bands are of prime interest.

In an infrared scanner, the detector area usually serves as the field-stop of a scanning radiometer. An optical filter is used to reject nonthermal radiation, such as reflected sunlight, which may confuse the observation. Rather than throw away this "unwanted" radiation, it can be used to measure other spectral characteristics of the scene. One way of doing this is to make the entrance slit of a multichannel, dispersing spectrometer the field stop of the scanner [6]. In this manner, each of an array of detectors in the plane of the dispersed spectrum "observes" the same resolution element on the ground but in a different spectral region. The spectral interval covered by each detector is a function of its size and location in the spectral plane as well as the dispersion of the spectrometer. The output of each detector can be used to generate a spectrazonal strip map of the scene. The instantaneous outputs from all the detectors represent a raw spectrum of the resolution element of the scene. These data can be processed and analyzed in real time.

The use of spectral information for mineral identification [1, 5, 9] and land-use, forestry, and agricultural surveys is under investigation [3, 8, 10]. The technique can be used wherever there are spectral-reflectance differences (water cloud versus ice cloud on the basis of absorption shift in the 1.8 μ region) [2], spectral-emissivity differences, or differences in thermal properties, e.g., observation of solar absorption versus thermal emission during the day.

As an "imaging" sensor capable of obtaining spectral data, the optical-mechanical scanning spectraradiometer has several unique features. The output signals from each detector are in electrical form, and, at all times, the signals come from the same resolution element of the scene. In short, there is no registration problem for extracting spectral information since the entrance slit of the multichannel spectrometer is the scanning aperture. The detectors are stable, linear, and have a dynamic range of the order of 10^6. The detectors can be calibrated periodically by observation of sources of known radiance. The calibration of a scanner for quantitative radiometric measurements is simpler than for a photocathode-type detector such as a vidicon or for a photographic emulsion. Each resolution element in a camera system is essentially a different detector, whereas the scene is scanned by a small number of detectors in the optical-mechanical scanner.

Since the data are being generated by an image-scanning process, the video signal has information on the spatial extent of a given object. Thus the data are amenable to some spatial discrimination and processing, or the output can be in terms of total area containing a given material (acres of wheat) or the result can be indicated by alphanumeric characters directly on a map.

The large dynamic range and linearity of nonintegrating quantum detectors used in scanners has a further advantage over integrating detectors such as photographic film. The scanner output can be readily adjusted to compensate for the washing out of contrast that arises from scattering. Basically the apparent radiance, N, of each scenepoint is given by $N = \tau N_o + N_s$, where N_o is the radiance at the surface, τ is atmospheric transmission, and N_s is the radiance of the scattering atmosphere.

For uniform scattering within the scene, N_s is a constant and produces a dc signal which can be readily biased out if its value is known or can be estimated. Using similar arguments, atmospheric attenuation can be compensated for with a gain change.

Using this technique, it is possible to generate a color image of the earth from space free from the excessive blue arising from Rayleigh scattering.

A line-scanning sensor such as the optical-mechanical scanner has several attributes that are less desirable than camera systems. Since the scene is scanned line by line, all elements in the scene are not observed simultaneously but sequentially. Therefore, any variations in spacecraft attitude must be known at all times if photogrammetric data are desired. For example, an attitude error of $\pm$ 1 mrad (3 min of arc) for a 200-nautical-mile orbit represents an uncertainty in the location of a given resolution element by $\pm$ 0.2 nautical mile.

Another limitation in scanners is that fewer detectors are used as compared with photographic film which has millions of detectors per square inch. Accordingly, the sensor has limitations in spectral and spatial resolutions determined by considerations of size of optics, number of detectors, and signal-to-noise requirements. One study [7] has shown that with a single scanning-aperture system (i.e., one detector per wavelength channel), the spectral region 0.3-2.5μ can be divided into as many as 30 channels. Each channel had a signal-to-noise ratio to detect changes in reflectance of less than 1 percent at wavelengths below 2.5μ and changes in temperature of 1°K (emissivity changes of about 2 percent). The above is obtained with a 6-in. aperture sensor having a resolution of 3 mrad.

The space, weight, and power specifications for a multispectral scanner system are highly dependent upon the spatial- and spectral-resolution requirements, the amount of on-board processing (see Section 3) conducted prior to storage or telemetry, and the method of data return to earth. A simple, 5-channel scanner having a spatial resolution of 1 mrad would require a 4-in. collecting aperture with cryogenically cooled infrared detectors. The scanner and detector electronics package would be smaller than 1 ft^3 and require a peak power of 15 W during operation. Using solid Ne cryogenics, a package 1.7 ft^3 weighing approximately 50 lb would be required for a full year of operation.

In summary, for relatively low spatial resolutions and correspondingly low data rates, the optical-mechanical line scanner and multichannel spectrometer can be mated to produce a sensor capable of measuring the spectral characteristics (0.3-15μ) in a scene. Pattern recognition techniques (see Section 3) can be applied to the multichannel data to decide whether an object or feature is present. Attenuation, scattering, and emission by intervening atmosphere degrades the spectral information, but the information should be retrievable by computer corrections based on expected albedo or observations of known objects. The applicability of the multispectral sensing technique to various user areas can be determined only by experimental investigations. One must determine the spectral characteristics of the object or feature of interest as well as its expected background since the latter will determine the false-alarm rate and hence the accuracy of classification. Thus, before the full potential of the multispectral technique can be exploited, considerable research is needed to prove the existence of spectral signatures and to develop signal-processing techniques.

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2.2 Radar

Radar, operating in the wavelength range between about 1 cm and 1 m, has the major advantage that it can produce fine-resolution images independent of the weather and time of day. Like any other part of the spectrum, this so-called microwave region provides shape information and unique "signatures" for different objects viewed. Since the ability to obtain the shape information is common to all the sensors having the same resolution, applications depending primarily on recognition of shapes and qualitatively on tonal differences detectable in the microwave region can utilize radar as their primary sensor, although further research is required to determine the significance of these tonal variations for object identification. Any sensor having adequate resolution and capable of operating at the appropriate times can be the primary sensor. The unique spectral signatures necessary for automatic and positive identification on a quantitative basis will require more research in all spectral regions, for both passive and active systems. More research is needed in the microwave region because less has been done on spectral signatures in this region than in the 0.3-15μ region.

Present-day fine-resolution radar is limited in its application to space primarily by power and antenna requirements. Truly fine resolutions require transmitter powers of the order of hundreds of watts although the amount of power required for some of the low-resolution requirements of meteorology and oceanography is surprisingly small. The power and antenna limitations are somewhat interchangeable, for larger antennas permit smaller powers if the same swath width is used. Most fine-resolution systems conceived for space use require at least a 4-m antenna, and longer ones are desirable. Another limitation of present systems, also somewhat exchangeable with the power limitation, is swath width. The simplest systems are roughly limited to swaths of 5 times as many kilometers as the antenna length in meters, although systems with wider swaths can be envisioned with some sacrifice in increased complexity. Powers of the order of 100-200 W during "on" time are feasible for the 100-200 ft resolution regime at present, and the powers of a kilowatt or so will permit improvement of the resolution significantly.

2.2.1 Polychromatic Systems

The preceding paragraph was based on the assumption of a monochromatic system, although the multiple polarization capability possible with such a system permits some of the advantages of polychromatic systems. It appears that to provide object or scene identification, advanced systems must incorporate a broad spectrum approach. Research in this field is needed to determine the advantages of use of different parts of the microwave spectrum for different applications.

In the past, radar systems have all been essentially monochromatic. The resulting images are analogous to optical images produced with laser illumination. Because of the nature of the scattering process, both a radar image and a laser-illuminated monochromatic image have a "pebbly" appearance; for any single resolution cell the image intensity is determined by a large-variance probability distribution (frequently a Rayleigh distribution). Ordinary photographs are produced with a wide spectrum of illumination, even when narrow-band filters are used; as a consequence, each resolution cell contains an intensity that is the wavelength average of the large-variance distribution, and the pebbly nature is not present. Use of a comparable broad-band illumination (panchromatic) in radar has become feasible due to the availability of decade-band antennas and octave-band amplifiers. Ordinary visible light covers a wavelength range of about 1.6-1; hence, use of octave-bandwidth radar equipment would be expected to give radar pictures in some sense comparable with those produced by panchromatic photography. Which of the almost seven octaves between 1 cm and 1 m will be profitable for various applications is not known at present.

Panchromatic illumination in the visible and infrared can be used to produce color images on film or can be subdivided with filters to produce multiple bands usable in signature analysis to establish the nature of the object sensed. A similar technique is possible with radar; that is, the separate bands illuminated by an octave-bandwidth transmitter can be treated to produce color images for automatic analysis of spectral signatures. Presumably a true multispectral orbital sensing system must use this technique, rather than confining itself to producing either a monochromatic or a panchromatic radar image.

Use of this "polypanchromatic" system, rather than a "polychromatic" system employing multiple monochromatic (single-frequency) radars is important for best use of automated signature analysis techniques, since reducing the variance of the individual components for a given resolution cell can greatly reduce the number of cells required to make identification decisions (see Section 3).

The spectral signature information in the visible region of the spectrum is due to molecular and atomic resonances, with some minor geometric effects. In the microwave region this role will be reversed; geometric effects will predominate, and molecular effects (on permittivity) will be less important. For example, the range of structure sizes in oak trees, conifers, and wheat is obviously different, and this different size range will yield different radar scatter spectra.

2.2.2. Resolution

Resolution with radar systems is determined by a combination of the ability to measure distance (time-delay) and direction (diffraction or Doppler velocity). The synthetic aperture technique permits resolution in azimuth to half the physical antenna length in theory. Obviously there are limits to the practical achievement of this goal, but over a long time frame, one can expect the theoretical to be approached closely. Realistically, it is probably not likely that resolutions much less than 10 ft will be achieved from space--although in theory one could do much better with a scanning antenna taking samples of small areas. Resolution in the range of the order of centimeters has been demonstrated in the laboratory (not on synthetic-aperture systems), and the only limitation on achieving this sort of resolution from space is the amount of power required, which would be very large indeed. Within 10 years, it is reasonable to suppose that resolutions of 10 ft or so will be achieved in both range and azimuth, and these can be achieved from orbits of heights up to 1000 km or more.

2.2.3 Registration and Image Quality

Most side-looking radar systems have been designed to produce single images, and little effort has gone into making the geometric fidelity such that superposition of multiple images is possible. Intrinsically, design of radar systems with good geometric fidelity appears reasonable. Fidelity in the range direction is, of course, subject to the radar equivalent of parallax displacement for objects at different heights (the top of a flagpole is closer and appears in a planar display displaced toward the radar). An image is produced by sweeping a cathode-ray tube, and errors are introduced by the imperfections in the tube and the sweep waveforms. In principle, these errors should be removable for an individual tube by a digital scan system employing sweep linearity and other corrections. The same system can change the slant-range display to a ground-range display (many radars do this somewhat imperfectly with appropriate analog circuitry).

Imprecision in azimuth for a real-aperture side-looking radar can be due to improper alignment of the sweep on the CRT with the film-drive mechanism, angular motion of the vehicle carrying the radar, and imperfect synchronism between ground speed and film drive speed for example. Because aircraft travel through a turbulent atmosphere, angular motions of the aircraft and variations in ground speed are random in nature, and servomechanical correction on both film drive and antenna are called for. With precise information on the motion of the aircraft, all these compensations can, in principle, be achieved; of course, more compensation means a more complex and costly system. Because the motions of a spacecraft are more regular and have a period that is long compared with those for aircraft motions, the compensation problem should be much easier in space. Synthetic-aperture systems are subject to similar problems, although the methods for resolving the problems may be different. These, too, should be easier to handle in space.

2.2.4 Data Handling

Synthetic-aperture systems require storage for the signal information in some fashion. Fully focused systems require large amounts of storage achievable only on film, dielectric tape, in storage tubes, or similar devices. The storage required appears great for digital devices, and the processing required is difficult for present digital systems to handle in real time. Present systems usually record the signal information on film for later processing, but development of improved temporary storage devices in the next few years should make a wider range of options available for processing. Furthermore, high-speed digital processing may be feasible in three years or so.

For fully focused systems, the required telemetry or storage rate is at least 2 lines per physical antenna travel distance. The number of elements in a line is determined by the resolution and swath width. Thus, a 4-m-long antenna, with 20-m range resolution, and 20-km swath width, requires at least 4×10^6 elements to be stored each second (2 MHz minimum video bandwidth). In many cases at least twice this bandwidth is required, and as additional spectral components and polarizations are added, the bandwidth requirement is increased accordingly. If this system were to aim at 2-m resolution, the bandwidth would be up by a factor of 10.

Semifocused and unfocused systems require less bandwidth because on-board processing (see Section 3) can reduce the bandwidth required to that for any sensor with the same resolution. This is feasible because the on-board processing for these systems requires less storage and can be simpler. Of course, when fully automatic on-board processing is available for all systems in a size and complexity that can be accepted, the telemetry and long-term storage requirements for the radar will be exactly the same as for any sensor with the same resolution.

2.2.5 Power Requirements

Power requirements for a radar system are due to the transmitter, the receiver and associated circuits, and the data-handling circuits. Only those for the transmitter can be readily calculated. The state of the art in electronic circuit design is changing so rapidly that it is difficult to estimate today what power will be required tomorrow for a given task. The transmitter, on the other hand, can never be more than 100% efficient, and the power required to obtain a given signal-to-noise ratio in the output can be computed from parameters of the problem (orbit height, swath width, resolution, and antenna size, for example). Transmitter efficiencies vary with the type of system used, but 25% efficiencies seem relatively easy to achieve today for many applications, and 33% to 50% efficiencies are possible in some cases. Thus, the estimated power requirement for the radar is made up of two to four times the estimated average transmitted power, plus an allowance for other circuits that depends to a large extent on the type of processing involved.

Fine- and moderate-resolution space radar systems almost always will involve synthetic aperture systems of some sort. The expression for the power required in such a system may take on many forms, depending on the parameters that are assumed.

So many parameters are involved in tradeoffs that a meaningful simple expression for power is not easy to present. Total system power drains of from about 50 to 300 W have been calculated for unfocused and semifocused radars. These systems operating in the 2- to 8-cm wavelength region at altitudes up to 800 km are capable of achieving resolutions of 30- to 100-m with swath widths in the 20- to 70-km region. When the resolution is improved to 15 m, and fully focused system is considered, the power more than doubles to the 400- to 700-W region. Additional polarizations and wavelength regions (the numbers mentioned are for monochromatic, monopolarization transmission) multiply the power requirements accordingly.

Weight and volume required by radars, exclusive of the antennas, are similar to those for other electronic equipment with comparable power drain, such as computer systems. Any of the systems described above could probably be built to weigh less than 100 lb, and the smaller ones should weigh as little as 25 lb. Volumes under 2 ft^3 are indicated, scaling down with required power.

2.3 TV Sensors

2.3.1 Spectral Range

While thermal infrared TV systems exist, their sensitivities and resolutions are not competitive with optical-mechanical systems at this time. Current high-resolution TV sensors are limited in wavelength response to the uv, visible, and near-infrared regions. Recently, it has been shown experimentally that semiconductor diode arrays can be used as detectors. This technology will be sensitive further toward the infrared. How far this and other methods can be carried into the infrared is not clear, but it seems reasonable to anticipate that in the future the long-wavelength limit will be extended as far as 1.5μ.

2.3.2 Advantages and Limitations

The prime advantage of a television sensor for space applications is that the signal is in electrical form and the photocathode can be used indefinitely. Thus the signals can be readily transmitted to the ground, and the total amount of data collected and returned to earth is limited only by the telemetry link and lifetime of the electronics and the satellite system. In contrast with photographic film, the TV system can operate long periods of time in the space environment.

While the resolution of television systems is constantly improving, the limitation in total information content per frame is limited by practical sizes of photocathodes. Current technology limits the photocathode size to 1 in. sq (a 2-in. -diameter tube). Technology for producing and using larger-area photo cathodes is being pursued. Resolutions of the order of 4500 TV lines (89 line pairs/mm) have been accomplished in the laboratory, and 6000 lines are projected by 1968. While this gives 3.6×10^7 resolution elements/frame, it is relatively small when compared with the resolution elements available on a 9 x 9 in. photograph. The dynamic range of television sensors is reported to be 100 to 1, and the sensitivity is 0.01 ft-candle sec.

2.3.3 Registration

To obtain tricolor imagery with a television sensor from a moving platform, three boresighted TV camera systems are required. Thus photogrammetric distortions are introduced by the different camera lenses and variations in the sweep velocities of the electron beam readout of the three TV tubes. Scan linearity of between 0.1% and 0.5% has been reported.

2.3.4 Data Handling

A 6000-line TV system has 3.6×10^7 resolution elements/frame. The sensitivity is such that a photocathode exposure of about 1 msec is required for good illumination conditions. The photocathode can be scanned at various speeds to accommodate either direct readout (present FM bandwidths of 4-5 MHz require a scan time of 5 sec) or tape storage. The video signal output is in a convenient form for subsequent processing either on board the vehicle or at the ground receiving station. Section 3 discusses some processing that can be performed on this signal on board the vehicle to reduce bandwidth and enhance the image control.

2.3.5 Weight and Volume

The Nimbus 1-in. vidicon camera weighs about 20 lb and has a power requirement of 19 W. It is estimated that the 6000-line, 2-in. return-beam vidicon camera will weigh 30 lb and require 30 W.

2.4 Photography

2.4.1 Spectral Range

Photography with silver halide film covers the near-infrared, visible and near-ultraviolet spectral regions, from approximately 0.3 to 0.9μ wavelength. The ultraviolet absorption of optical glasses limits the useful range in practice to about 0.4 to 0.9μ; however, the actual absorption in a particular lens will depend on the type and thickness of glass, and in some cases appreciable uv is transmitted. Infrared absorption is not normally a significant factor, though in some systems with very thick glass windows there could be appreciable energy loss.

Typical panchromatic aerial films cover the spectral range 0.3 to 0.7μ, the variation in absolute spectral sensitivity over this range being $\pm$ 0.3 logarithmic units from the mean level. Infrared aerial films overlap the visible range and have substantially uniform sensitivity from 0.7 to 0.85μ.

2.4.2 Advantages and Limitations

Photography's advantages are high resolution, metric accuracy, information easily and quickly read out by human interpreters in a qualitative and semiqualitative form, current availablility of equipment and handling techniques, and relatively inexpensive and compact apparatus. Its disadvantages are inability to penetrate clouds or to operate in darkness, necessity for film recovery and no real-time information, and information not directly available in electronic form for quantitative data handling.

Proposals have been made for capsule recovery of film, and there is no reason to suppose that this is a serious problem.

Hybrid photographic/TV systems can be used for a closer approach to real-time information, but the value of these in comparison to tape storage or real-time TV is doubtful when the total volume of information is substantial or a quick look is necessary.

Photography's main advantage is its high resolution, which may be expressed another way as the ability to record relatively fine detail on the ground in a relatively small satellite-borne apparatus. Resolution is a useful concept when comparing systems that are orders apart but is very far from giving a full description of image quality. Some of the problems involved are discussed in Section 3; here it is only necessary to advise caution in comparing, say, photographic and television systems, or even different photographic systems, when the nominal resolutions come within a factor of two. Two other general points on resolution are relevant. First, since photography uses optical lenses there is a tendency to project systems in terms of possible resolutions based on aperture and wavelength. Thus a 12 in. f/4 lens has a theoretical limiting resolution of, say, $\frac{1600}{4} = 400$ lines per mm, which could certainly be observed in the aerial image. But the resolution achieved in practice depends on the modulation transfer function of the lens, not its limiting resolution, and the MTF's of even the finest lenses do not approach theoretical. The quoted lens could achieve 100-200 lines per mm with the best available film.

Second, resolution is liable to be different between visible and infrared, and between different wavebands of visible. There is no obvious reason why infrared film should not be made with resolution on the same order as panchromatic, but considering present readily available films, we find the following maximum resolutions:

Infrared	65 lines / mm
Panchromatic of equivalent sensitivity	100 lines / mm
High-resolution panchromatic	500 lines / mm

In general, lenses are not corrected for infrared and give somewhat inferior performance even when refocused. The best refractive lenses are corrected for the "minus blue" range, say 0.5 to 0.7μ, and performance deteriorates outside this range. However, these problems would not be serious at the resolution level of 100 ft required for land use (100 ft$\sim$30 lines/mm for a 6 in. lens at 100 miles).

There is no doubt that photography can offer the highest resolution of currently available systems. The ultimate resolution will presumably be determined by atmospheric inhomogeneity, and for a vertical line of sight a few inches on the ground may be possible. The actual resolution obtained will be largely a question of size and, hence, cost. For most of the applications in earth resources, the required resolution is well within photographic possibilities. It would be quite reasonable to expect 150 lines per mm from a system of 36 in. focal length with enough sensitivity to operate at solar altitudes greater than, say, 10 deg. This translates to 8 ft on the ground, which is an order better than is required for, say, agriculture. To obtain this 8 ft consistently over a large area would involve problems of camera design and use, but we can reasonably expect to solve these problems. For example, accurate image-movement compensation and exposure control would be essential, but known devices could be applied. However, for the 100-ft resolution typical of earth resources needs a smaller camera of lower performance would be adequate and would cause fewer problems in data handling.

2.4.3 Registration

Accuracy of registration is closely allied to resolution in multispectral band systems. Tripack photographic systems obviously have the advantage that there is no registration problem. Photographs taken by separate cameras can be printed to give color images, or the separate monochromes can be examined by more quantitative means. Experience has shown that the registration problems in printing or due to film-base distortion are not serious, but the exact matching of several cameras is not a trivial problem, even at the low resolutions required. However, for quantitative photometric evaluation the question of registration is not likely to be serious, since one record could serve as the map reference for all.

The camera-matching problem involves:

a. Matching focal lengths: Lenses vary by a few percent and even with selection exact matching is not possible. Subject to uniform distortion in all lenses, focal-length differences can be taken out in printing.

b. Distortion: All lenses suffer from some distortion, less than 0.1% in mapping lenses, 1% or more in other lenses. The serious factor would be the variation of distortion from one lens to another, especially when different spectral bands are involved. Data are not available, but experience suggests that below 20 lines per mm no great trouble will be found.

2.4.4 Data Handling

Photographs are traditionally examined by human observers specializing in some particular application, and this will probably always be necessary to some extent. Earth-resources users suggest other approaches, however.

For example, if all vegetation in tripack ir color pictures shows red, the relative area per frame could obviously be integrated by an optical device working on the red. Similarly, water or snow area could be measured by working on black or white levels. In principle, quantitative evaluation of tonal differences by photographic photometry is possible, but the experimental difficulties of this should not be underrated. Especially when small details are concerned, photographic photometry is not a very accurate procedure, as so many nonlinearities are involved.

One important aspect of traditional data handling is dissemination. If copies of color ir photographs are to be made available for wide distribution, very good duplication techniques will be required to minimize the inevitable tonal and resolution losses. This may be an argument for a facsimile type of reproduction, putting the data of the original picture on tape, at least for some areas, as soon as it is available. Since it is to be expected that the photographic data retrieved by satellite cameras will be useful to many different disciplines, there is scope for research to find the most efficient duplication and dissemination methods.

2.4.5 Weight and Volume vs Performance

The area of film required is obviously proportional to the area of ground to be covered. As expressed by Katz:

$$\text{Film area (ft}^2) = \frac{2.8 \times 10^7 \text{ ground area}}{S^2} \text{(miles }^2)$$

where S is the scale number.

$$\text{Film area (ft}^2) = \frac{300 \text{ ground area (miles 2)}}{R^2 G^2}$$

where R is resolution in lines per mm on the film and G is ground resolution required.

For the low resolutions specified for most earth-resources applications the area of film required is very small. Thus for 10^6 sq miles at a ground resolution of 100 ft and a film resolution of 30 lines per mm (6-in. lens at 100 miles) the required area of film is 30 sq ft—say 200 ft of 70 mm film. The weight would be less than 2 lb, even for thick-base ir color film. The corresponding camera would occupy 2-4 ft^3 with mounting of controls and would weigh around 300 lb. Film-ejection devices would add weight and bulk, but this need not be excessive. Power requirement would be about 100 W intermittent.

The area and volume of both film and camera increase rapidly with resolution.

One conceivable system would use about 20 lb of film per 10^6 sq miles and the camera would occupy about 10 ft^3 and weigh on the order of 200 lb.

2.4.6 Dynamic Range

Photography's dynamic range is conventionally specified in terms of the H and D curve, density versus log exposure. While this refers to the negative, it is implicit that anything recorded on a negative can be reproduced on a positive transparency. In principle it is also possible to obtain satisfactory positive prints on paper, because the luminance range of a good bromide or chloride paper (say 5 to 1) is much greater than the typical luminance range (say 6 to 1) of a view seen through the whole atmosphere in the clearest air. However, the common practice of working to a gamma of 2 or more, and the complications of the nonlinearities of negative and positive emulsions, result in paper prints that are less linear than transparencies.

The straight-line part of the H and D curve in aerial films covers a log luminance range of 1.0 (10 to 1 range). In practice, exposure cannot be controlled with sufficient accuracy to locate the image invariably on the straight line. Moreover, the premium on exposure tends to push the densities down to the toe more often than not. This is even beneficial, since a gamma of 2.0 is too high for vertical photography on clear days. The working dynamic range is thus greater than 10 to 1, say 32 to 1 in practice.

So far, we have considered the range on large film areas, i.e., large relative to the resolving power. Obviously, at the resolution limit there is no dynamic range, and for intermediate sizes it must fall off more or less parallel with modulation transfer function.

2.4.7 Linearity

The straight-line part of the H and D curve is commonly held to represent "linear" reproduction, but this is only true for a positive reproduction in which the product of negative and positive gammas is 1.0. Curvature in one characteristic can be compensated by inverse curvature in the other. If gamma is greater than 1.0 (or less) the reproduction is not linear, even if the densities be wholly on the straight line. In practice the negative density range usually includes part of the toe, so a further nonlinearity is introduced.

When microdetail tending toward the resolution limit is considered, further less controllable nonlinearities occur, due to developer adjacency and other effects. These cause an effective increase of gamma for certain size ranges, offsetting to some extent the loss of contrast due to the MTF. In some emulsions the MTF as a whole is strongly dependent on exposure level, and it also varies to some extent with color of light.

The overall result of these nonlinearities does not normally cause any problems; in fact for broad-band photography, some nonlinearities are quite beneficial. Difficulties are bound to arise if accurate photographic photometry is required. However, to put this in perspective, it should be pointed out that the nonlinearities discussed are trivial compared to the enormous distortions of luminance relationships caused by atmospheric haze. For example, true color reproduction is only possible if the characteristic curves of each layer are straight, parallel over the whole dynamic range, and at a gamma of 1.0. The inevitable compromises are quite acceptable for qualitative or semiquantitative work but would rule out accurate colorimetry from aerial photographs. Any such errors, however, are completely dwarfed by the errors due to haze which, as the Gemini photographs show, can eliminate color discrimination altogether, even in clear conditions.

2.4.8 Stability of Sensitivity

Regular panchromatic aerial emulsions are very stable, especially relatively slow high-resolution emulsions likely to be used in satellites. At normal temperatures, say not exceeding 90°F, they are not likely to lose speed to any serious extent over a year. They will, in fact, stand short exposure to much higher temperatures, up to, say, 140°F. Very low temperatures cause a slight reduction of sensitivity which returns at normal temperature.

A slight fading of the latent image occurs after exposure, but most of the loss takes place in the first few hours after exposure, so there is no reason to expect serious losses of apparent sensitivity when film stays in orbit for many weeks.

In general, infrared and color films are less stable, infrared in particular being more affected by high temperature. Full data are not available, but it is certainly desirable to stabilize the satellite temperature, not exceeding 90°F for long periods, if infrared film is carried.

Radiation fogging, if serious, is equivalent to a loss of speed and dynamic range, coupled with degraded resolution. So far there is no available evidence that radiation is a serious matter, at least for 100-200 mile orbits. Further information is needed about higher orbits, 500 miles or more. For the low orbits that would probably be used for photography we can reasonably assume no trouble for missions lasting many weeks, at least from natural radiation.

2.5 Microwave Radiometry

Microwave radiometers operate over the same range of wavelengths as radars (1-300 mm). However, like thermal infrared radiometers, they sense thermal emission from objects rather than reflected self-generated illumination as radars do. As might be expected, microwave radiometers have some of the properties of infrared radiometers and some of the properties of radars. These common properties are listed below.

2.5.1 Microwave and Infrared Radiometer Properties that Are Similar

1. They are sensitive to temperature and temperature gradients. Emissivity corrections are greater in the microwave region than for infrared.
2. They can "see" absorbing objects such as clouds and fog and measure their temperature and other properties.
3. They can "see" homogeneous, partially transparent objects such as gases and measure gas amount, temperature, pressure, and velocity. The magnetic field present at the location of the gas can sometimes be measured by Zeeman splitting of the emission line.
4. They are sensitive to emissivity variations and, therefore, absorption.
5. They can frequently identify surfaces by variation in emission with wavelength, polarization, and viewing angle. These variations are more dependent on the complex dielectric constant of the surface and hence the surface material itself, than in the ir or radar case.

2.5.2 Microwave Radiometer and Radar Properties that Are Similar

1. They can penetrate clouds and rain. The microwave radiometer is the only passive, all-weather sensor. Data correction is larger in magnitude and more difficult than in the radar case. Penetration is less than that of radar due to the smaller thermal power radiated by objects compared with typical powers reflected due to radar illumination.
2. They can "range" by rejecting all emission, except from emitters on a surface of constant differential delay to two base stations of a correlating radiometer. However, these emitters must be point emitters in order to produce a signal in a correlating radiometer.
3. They can measure velocity by Doppler means in correlation radiometer configurations.

The all-weather nature of microwave radiometers makes them capable of measuring the temperature, pressure, wind, and cloud-density profiles of the atmosphere in regions where weather is present. None of the quantities can be measured by a radar. The presence of weather makes their measurement by infrared impossible also.

In a like manner, microwave radiometry can measure ocean-surface temperatures and surface-temperature gradients (proportional to heat flow out of the sea) on an all-weather basis. Again only microwave radiometers have this ability.

In addition, microwave radiometers can measure sea-surface roughness and precipitation amount and nature. However, radar is probably better adapted to carrying out these measurements.

In the case of surface identification by multispectral sensing, microwave radiometry is very useful when paired with radar measurements, for the radiometer measures absorptivity that is characteristic of the surface material. Radar, although its return depends on the material permittivity somewhat, is much more dependent on surface texture. When both instruments are used, the surface is more completely characterized than is possible with either instrument alone.

Microwave radiometers are basically small instruments using little power and occupying only a cubic foot or so. Their antennas, however, vary greatly in size and weight depending on the resolution required, scanning requirements, and polarization specifications. They can vary in weight from a pound or so to nearly a hundred pounds and in size from a few inches on a side to tens of feet on a side.

2.5.3 Data Handling

Dynamic range, as in the case of all sensors using cathode-ray tube readout to form images, is limited by the cathode-ray tube to 13 to 15 dB. The dynamic range of the signal itself is about 40 dB.

The output bandwidths encountered vary from a few cycles to hundreds of cycles in monochromatic mapping radiometers. If a number of bands are used for multispectral identification, the total bandwidth will be the number of frequency bands times the monochromatic bandwidth.

The radiometer strip image has one range coordinate and an angle coordinate like an ir strip map, rather than two range coordinates like a radar strip map. As a result, a special radar using the same antenna as the radiometer and locating terrain points by means of the antenna beam resolution, like the radiometer, should be used to obtain registration between radar and radiometer images for multisensor identification methods.

It might be added that radiometer signals do not scintillate like standard radar signals, since thermal emission is not coherent like radar illumination. Therefore no special pains need be taken to average out scintillation effects such as are required in the radar case.

2.6 Laser Illumination

It has been suggested that laser illumination might be used to provide pictures of the earth's surface at night from satellites, either by photography or electro-optical sensors. This does not appear at all promising in the present state of the art, except for very small areas of earth surface.

As an example, consider direct photography through a clear zenith atmosphere using a very fast film and a lens system of large relative aperture. Using illumination of 1 watt per square foot of earth surface concentrated at a wavelength at or near the peak of film sensitivity (visible or near-visible spectrum), an exposure of 1 millisecond should be adequate. In other words, 1 millijoule of illumination energy will be required, independent of the scale of the photograph and of the exposure sequency selected (i.e., simultaneous exposure of the entire picture area or sequential scan). This leads to 28.8 kilojoules per square mile, or an average laser power output of 28.8 kilowatts to photograph only one square mile per second. Such an average power output in or near the visible spectrum from a laser that might be carried on a satellite is beyond the present state of the art. Even if it were not, so small a coverage rate as one square mile per second would be orders of magnitude below the requirements of the earth-resources programs now envisioned.

The use of some of the newer electro-optical sensors involving image-amplification devices would require much less power than the direct photographic example given above. Nevertheless, it seems quite unrealistic to consider laser illumination for this application unless, and until, marked advances are made in laser technology or in sensors, or both.

3.0 DATA SYSTEMS AND DATA PROCESSING

The following discussion is an attempt to place the data-systems requirements for the various disciplines in proper perspective. Each discipline* has indicated the form of the user data required. Generally the requirements for the first-generation system appear to be for hard copy prints of the sensor outputs. The sensor subsystems include cameras for color photography and high-resolution (side-looking) radar for coverage over clouded areas. In addition, the possibility of a three-camera TV system capable of 100-ft resolution is being considered. These requirements are outlined in brief form, then the data-link and data-processing systems anticipated to meet these requirements are discussed.

The user output for the second-generation system, as well as the sensors' configuration, is less well defined. The data-systems discussion takes advantage of the opportunity to discuss methods of analysis that can be used to convert the input data to readily usable output information. A system configuration is outlined, data-link channels are suggested, and multispectral and multisensor data processing are considered. Possibilities for on-board processing are discussed taking advantage of the development of compact, large-capability, general-purpose computers. In addition, automated data processing with special-purpose computers is considered, and recommendations for R&D are presented.

3.1 First-Generation System

Several data forms are anticipated for this system with the requirement of data dissemination on a quarterly (or at best monthly) basis. The following indicates a methodology for collection and processing each data format consistent with the user's request.

Photographic Data

1. Capsule recovery
2. Time and some ephemeral data placed automatically on film track during exposure
3. Development of prints and attaching "precise" coordinate, scale, resolution, and time data
4. Indexing and storing according to region, time of year, time of day, and other appropriate designators
5. Overlay and viewing of specific frames with available projectors and viewers to generate an uncontrolled, or perhaps, a controlled mosaic
6. Disseminate copies of each frame of data recovered to users
7. Respond to requests for selected frames or uncontrolled mosaics of selected regions

*This does not pertain directly to meteorology or oceanography.

Modest-Resolution Synthetic Aperture with On-Board Processing

1. Data Link: transmit stored data at 200-kHz bandwidth, FM (see Appendix C)
2. Receive on analog tape and correlate with ephemeris and radar antenna pointing data
3. Use analog signal to modulate an electron beam (flying spot or CRT) and expose strip film with the modulated beam to generate radar map; place coordinate, timing, scale, resolution, and other data on film strip
4. Develop film strip of radar map
5. Index and store according to region, time, and other selected designators with companion photographic maps
6. Disseminate to participating users single frames or strips as appropriate
7. Generate uncontrolled mosaics per users' requests
8. Respond to other requests for frames or mosaics

TV Camera Data

1. Collect data by scanning vidicon output and store on magnetic tape, insert timing and position information as appropriate on tape
2. Transmit recorded data via FM link (4.5-MHz bandwidth) and record on FM recorder
3. Reconstruct image using laser reproducer or flying spot scanner and film
4. Place identification marks on frames (time, positions, resolution, etc.)
5. Index and store resulting frames
6. Digitize analog data for storage with identification.
7. Generate two- and three-color frames from single (three-camera) frame combination (optically or digitally)
8. Index and store resulting frames
9. Disseminate single-camera and two-, three-camera reconstructions to users as required
10. Generate uncontrolled mosaics of selected areas at users' requests
11. Respond to individual users for single or two-, three-color frames

Radar Scanning Data--Fine-Resolution Synthetic-Aperture Radar*

1. Record analog radar signal on film strip using imaging beam recorder
2. Record simultaneously edge track information on radar characteristic and satellite ephemerals
3. Capsule recovery

*On-board processing of fine-resolution data may be feasible; if so, procedure listed for "Modest Resolution Synthetic Aperture with On-Board Processing" would be followed except that the data bandwidth will increase to correspond with improved resolution.

4. Generate high-resolution synthetic-aperture radar imagery using optical processing
5. Insert or record ephemeris data as well as time, position, and resolution data on each frame or strip
6. Index and store resulting frames or strips
7. Disseminate to users
8. Respond to other requests for selected frames, strips, or specific uncontrolled mosaics

Data-link and data-processing requirements for the above appear to be limited to an FM telemetry system of ~4.5-MHz bandwidth. Coverage can be handled by two or three ground stations. Ordinarily, data-processing installations are not concerned with the details of communications links except as they bear upon the equipment necessary to convert analog signals to data formats—digital or display, data volume, or data rate. For the first-generation system under discussion here, a 4.5-MHz link is anticipated to accommodate the radar video and a low-rate PCM or PAM for a housekeeping link. It is worth observing that housekeeping need not be transmitted continuously but, assuming that 120 eight-bit words per second will suffice, can be played back in a 6-min interval once per 90-min orbit using, say, the appropriate IRIG 15% proportional subcarrier. Stations must be equipped with FM receivers and analog recorders. The processing station must have a limited optical processor lab to accommodate map generation of the side-looking radar (SLR) and the images to be generated from the vidicon camera. A flying-spot or laser-beam scanner, optics bench, and photographic processing lab seem to be adequate.

Teletype links should be maintained with the appropriate agency for receipt of ephemeral elements and/or other orbit-determination information. This information should be received at the processing center in timely fashion, i.e., no later than the arrival time of the prime data-analog tape or film.

Ephemeris information could be generated on-line using a high-speed general-purpose digital computer rather than by ephemeris-tape merge. Existing state-of-the-art trajectory programs could be used and a minimum of redundant software development undertaken. (Computing times for 90-min orbits are currently about 0.3 min at a rate (absorbing overhead) of about $3.60 an effective computing minute. The costs of generating ephemeris tapes is absorbed in the cost of the tape ($25.00), the storage costs, and other handling costs, and the high probability of a requirement for a tape-regeneration run due to deterioration.

Film chips* should then be generated for each frame or strip etched with the controlling data, and indexed. The large general-purpose computer should be available for indexing and retrieval and a reference manual generated and updated as required. Hard copy of the prints will be generated and sent to the user. A program should be written to prepare uncontrolled mosaics from a small number of frames upon request.

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*Film chips as developed and used at the Rome Aeronautical Development Center (RADC) are recommended over microfilm or hard copy positive or negative. Though costly, they are less subject to deterioration, warping, and wear and are readily stored and capable of automatic retrieval.

For the three-camera TV system a special optical bench arrangement will be required to generate the two- and three-color prints. This should be done at user's request. It may be possible to perform this operation digitally. If so, a requirement will exist for A/D conversion equipment. A computer program must be written to perform this operation and the resulting data converted to photographic form via a D/A converter and film scanner.

For the SLR, a special optical imaging system will be required. It may be possible to do this processing in the computer as well, although it is anticipated that some research will be required to specify how this operation can be done digitally.

For the film-capsule recovery the film must be developed and identification marks added on each frame. Hard copy should be generated and sent to users. Film chips will then be prepared and the frames stored.

The computing center (Figure 6. 3. 1) requirements seem to necessitate a photographic processing laboratory, and an optical laboratory with laser, flying-spot, or beam recorders and with peripheral equipment to allow the insertion of identification marks on each frame. The photographic lab must have the capability of generating both film chips for storage and hard copy for distribution. A general-purpose computer should form an integral part of the indexing and retrieval system and will be required to generate reference catalogs, on a timely basis. A second general-purpose or special-purpose computer must be available for preparing mosaics and perhaps performing the two-, three-color image processing and the SLR image processing.

The first-generation data-systems* requirement has been briefly discussed above and appears to pose little or no problem to the state of the art in any facet of the related areas. The required telemetry systems have been flown, the ground-station requirements exist or can be obtained, and the computer and peripheral equipments are available items. The principal emphasis must be placed on data management and the generation of software for indexing frames as received and establishing a storage and retrieval system for immediate access of individual frames. A procedure, either software or through the use of peripheral imaging systems, for generating uncontrolled mosaics on a selected basis and for generating multicolor prints from single-color frames must also be developed. The former can take its cue from the Weather Bureau CDC6600 rectification and mosaicing programs. The latter will require development of special hardware for correcting the camera biases and nonlinearities and for the rapid registration of images and will require the development of a wide-band recording medium (storage tube).

A program for the planned growth of the ground data-processing station must proceed in parallel with that of the satellite system. As the latter evolves through successive generations, each more sophisticated than its predecessor, so must the data-processing system evolve, pari passu, in order to realize the maximum in information yield promised by the more elaborate and presumably more capable sensing systems. In this regard a

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*Data systems for this discussion will include data processing, data link, formatting, output, and the other operations necessary to provide the user with an end item from the sensed signal.

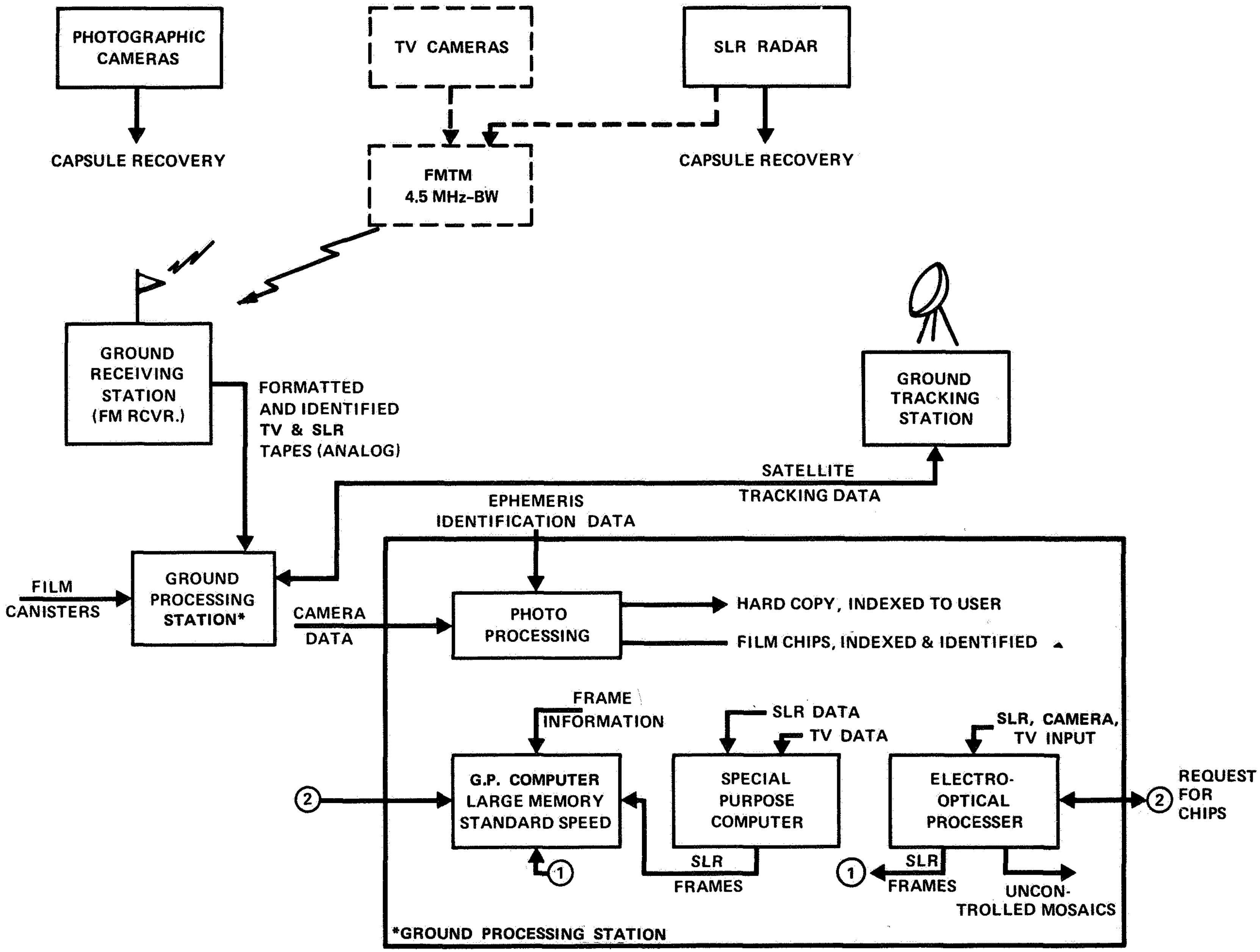

FIGURE 6.3.1 First-generation data link and data processing.

difficulty nearly always arises: the expenditures for replacement of data-reduction and processing equipment are made only with the greatest reluctance. The danger here is that economic constraints in this part of the total sensing-data-processing complex will constrain the total system capability. While this situation cannot be avoided altogether, planned growth of modular configuration can help to minimize the difficulty. With this in mind the following recommendations are offered:

1. A general-purpose computer should be used for ephemeris calculations as required—indexing and rectification—and it should be a member of a family of larger computers and have "upward" software, interface hardware, and peripheral compatibility with the more powerful planned or actual members of its computer family. It should not be an "end-of-the-line" computer.
2. In processes such as digitizing from analog tapes and PCM formatting there is considerable latitude when it comes to dividing the total task between hardware and software. From a growth standpoint the software is superior. Expensive special-purpose hardware should be avoided and as much of the burden placed upon the general-purpose computer and its concomitant software as possible. (Software is under development today that accommodates high-rate PAM, SSB, FM digitizing, and PCM formatting on a general-purpose computer with a minimum of interface hardware.)
3. The first-generation system configuration discussed does not provide for digitized data in large quantities—the basic requirement is for photographs. In the future, however, as analytical techniques for extracting the ultimate information from the data advance in capability and user confidence, this requirement is almost certain to change with growing emphasis on digital processing. It is recommended that techniques enabling digitization of the source data (film chip)* should be developed. Such development facilitates adaptation of the first-generation configuration to second-generation requirements.
4. Only computer systems with multiprogramming capability should be considered. It is an established fact that high digitizing rates 150,000 SPS (12 bits) can be carried out as a background operation with high-speed computer programs running in parallel.

3.2 Second-Generation System

The second-generation system as envisioned by the various disciplines allows a better utilization of the data-systems technology and takes advantage of the giant strides made in recent years in the development of computers and methods for data analysis.

Numerous sensors have been suggested to obtain both radiance and spectral reflectance measurements from which characteristics of the imaged area can be determined for subsequent classification. The introduction of multiple sensors is expected to increase the data-link requirements.

*Because of its large data content per unit volume, relative permanence compared to magnetic tape, this photographic artifact has considerable merit as a bulk-storage device.

The hypothetical system includes high resolution (100-ft cells) and swath widths of 100 miles with 6 bits per sample for each of the following:

Line (slit) scanners
Multispectral radar
High-Resolution Infrared Radiometer (HRIR) and Medium-Resolution Infrared Radiometer (MRIR)

Due to the high resolution and possibility of an automatic digital-computer processing, these instruments are candidates for pulse-code modulation (PCM) transmission. For a 90-min orbit each will require a link with 1.12×10^6 bits per second (bps) capacity. These link capacities are in line with reasonable 1970 expectations.

Multispectral TV and high-resolution (HR) radar are candidates for FM transmission with an expected bandwidth of 200 kHz or more.

Passive microwave requirements are comparable with "housekeeping" bit rates and can very likely be subcommutated on the PCM links.

Duty cycles for the several candidates of a PCM transmission are not determined at this time; however, time multiplexing via stored-program variable-format PCM systems is a possibility worth exploring once these duty cycles have been established.

In those cases where excessive bandwidth may be required, such as for the photographic camera systems, the use of multiple reentry systems can accommodate the needed data acquisition if the frequency of data acquisition is not too high (i.e., monthly or quarterly). The possibility of on-board processing of portions of the data acquired may be of further use for both bandwidth reduction and reduction of ground data-processing requirements.

With the availability of computers with large memory capacity and processing times comparable to large general-purpose computers (Table 6.3.1) a significant amount of data processing can be accomplished on board the vehicle. The relatively high bandwidth requirements make real-time data compression attractive. The basic reason for real-time processing is to avoid saturating the parallel I/O capacity of the computer which is occasioned by slow digital tape-deck transfer rates and the resulting excessive tape-handling problems. The only decision that has to be made is whether to do this in orbit or on the ground. Obvious weight and power considerations favor the ground installation; however, since three ground stations may be required, the equipment necessary to relieve the awkward tape logistic and handling problem (20 megabits per second (Mbs) is approximately one 800-bits-per-inch (bpi) digital tape every 5 sec) must be provided in triplicate or the equivalent in analog tape must be shipped physically to the processing center. Further, the real-time processing effects no bandwidth savings in the orbit to ground-level bank.

Real-time processing in orbit, despite the disadvantages of adding to the vehicle weight and power consumption, is attractive from the standpoint of bandwidth savings and does avoid equipment complications. The equipment is, however, lost when the vehicle expires.

TABLE 6.3.1

SPACEBORNE COMPUTERS

Characteristic	Current[a]	Projected 1970-1975
Core size	131 K @ 32 bits	250 K
Word lengths	16, 32, 64, 48, 30	Same
Memory cycle	1.0-2.0 μsec	10^{-3} μsec
Index registers	8-16	Same
Add times	1.0-5. μsec	10^{-3} μsec
Multiplication times	6.5-18 μ sec	6×10^{-3} μsec
Division times	8.0-32. μsec	8×10^{-3} μsec
Floating points	Hardware	Same
Elementary functions	Hardware	Same
Weight	75-520 lb	
Volume	1.8-7.0 ft^3	
Power	365-809 W	

[a]The specifications given here are composites and represent reliable "on-the-shelf" computers used in aircraft and proposed for existing orbital vehicles; they do not represent "state-of-the-art" computer technology.

No attempt will be made here to separate those tasks that can be done on board the vehicle from those relegated to ground-based processors. Rather the discussion will consider the multispectral and multisensor processing that can be accomplished in general. The separation of where the processing is to take place is relegated to user stipulation or specific examples shown by illustration.

The system envisioned will take the form shown in Figure 6.3.2. The detailed discussion of the data processing implied is beyond the scope of this discussion. The intent here is to give some insight into the kinds of data processing and data reduction that can be envisioned for the second-generation system. At first glance it would appear that the volume of data that can be acquired would soon cause a bottleneck that would nullify the wide and repeated coverage achievable from the satellite. The first-generation system, however, has by this time established a procedure for handling the incoming data and assuring that users are provided hard copy on an immediate, routine basis. The expected increase in volume and type of imagery to be made available will involve some drastic changes, but one line of flow should be open, that of generation of copies of the original imagery properly annotated and indexed and stored in a readily retrievable format. This portion of the data-processing system can be expanded at a more leisurely pace, commensurate with the increase in data-input rate. The peripheral equipment that has been

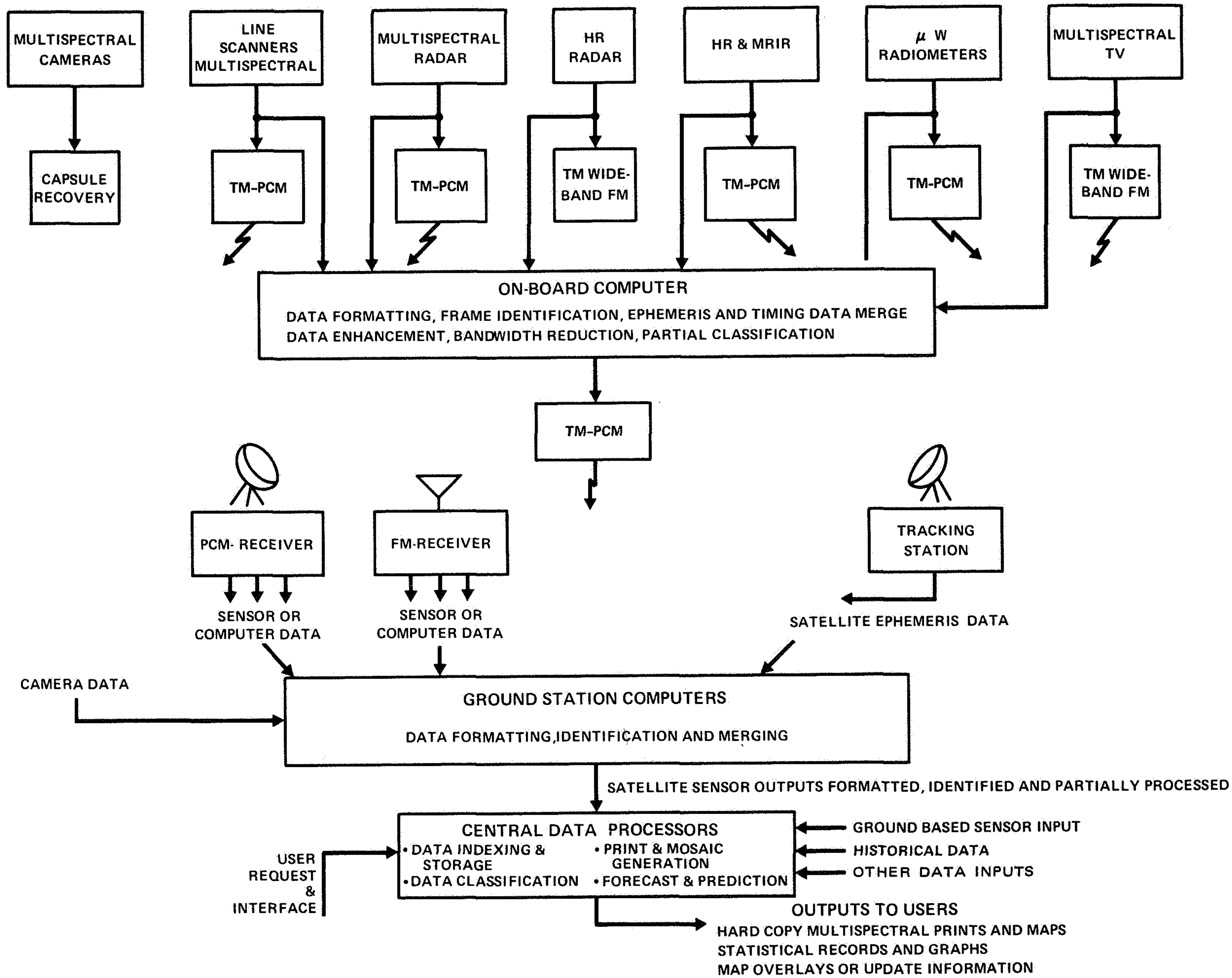

FIGURE 6.3.2 Overall view of second-generation system.

used to generate hard copy, film chips, and uncontrolled mosaics from the TV camera, SLR, and photographic imagery has immediate use in the second-generation system and will form the focal point for the expansion of the equipments and activities to handle the multispectral, multisensor data anticipated.

Fortunately, it is not likely that each user will want all the data immediately after it has been acquired. Rather it appears that specific users will have identified sensors that benefit them most and require a quick turn around on that data only. They may request additional data, but they will be willing to accept this on a less timely basis since it will be needed principally for support or verification or may be required only for their aesthetic, academic, or long-range scientific interest. Other users have requirements that are met by an intensive effort for a short period of time at infrequent intervals (seasonal variations, for example). Their need is immediate, but, rather than a step function input on the work load, it is more like an impulse, and provisions must be made to introduce the additional processing equipments needed for the short-period, high-quantity data handling that will be required. Those users who have specified the needs for multispectral or multisensor imagery on a routine basis on shortly spaced intervals will pose the greatest demand on the processing centers. However, since their demands are greater it seems reasonable to assume that they can be specific as to the final requirements. It is here that the automated data handling and data processing should offer the most benefit. The output is no longer the sensed signal converted to a form that is manageable by a user, but leaving the burden of all manipulation, conversion, and computation on his shoulders. Now one can foresee the possibility of the preparation of the annotated maps, the land-use surveys, the compilation of grain forecasts and crop-yield statistics, or the prediction of sea states on shipping lanes or storm warnings in the tropics. The users, both scientists and laymen, can now be provided with meaningful information on a timely basis. The response of an automated data-handling system is not to be limited to processing requests for data desired from a fixed-cycle data-gathering system. Indeed variable formats, raised on command to accommodate special critical needs are within current capabilities, and there is every indication to support the belief that the development of this feature of satellite-borne instrumentation will expand between now and 1970.

3.2.1 The Automatic Processing of Data to Produce Useful Information

The remaining discussion will concern itself with the concept of automatically processing multispectral and multisensor imagery to obtain an identifiable end-item output. Attempts will be made to illustrate a range of possibilities as well as indicate the areas of anticipated difficulties that may prove helpful in suggesting R&D to be accomplished.

The multispectral imaging system (optical line scanner) (D. Lowe, University of Michigan) can provide frequency information, on the scene being viewed, over a wide range covering the 0.3 to 15μ band. In such a system each detector of the spectrometer observes the same resolution element of the scene but in a different wavelength region, eliminating the multisensor registration problem. Each detector's output is a video signal corresponding to the scene brightness in the particular wavelength region of operation. The possibility of discriminating material composition from the spectral distributions of its radiation seems quite reasonable. It has been demonstrated that the determination of spectral signatures for distinguishing between landscape features, minerals or rocks (R. Lyon, Stanford Research Institute), and farm crops (D. Landgrebe, Purdue), for example, can be accomplished on a limited basis. The rapid processing of the output from the line scanners, even on board the satellite, can be readily accomplished. Each detector's output can provide an input to a classification system. The system itself could consist of a correlator against which the sensed signal is compared with a reference function or signature. The linear operation of cross- or autocorrelation has proved extremely useful in similar tasks. The correlation function

$$\phi_{fg}(x_0) = \int f(x)\, g(x-x_0)\, dx$$

is computed and is a maximum when g(x) and f(x) are the same and properly aligned. For the case being considered the function becomes

$$\phi_{fg}(\lambda_0) = \int_{\lambda_1}^{\lambda_2} f(\lambda)\, g(\lambda-\lambda_0)\, d\lambda,$$

where $g(\lambda)$ is the signature of a specific landscape feature or farm crop and $f(\lambda)$ is the output from the detector's array. A number of such correlations can be computed simultaneously and rapidly and the classification of the scene or resolution element being used assigned by the correlators with the maximum output, as shown in Figure 6.3.3.

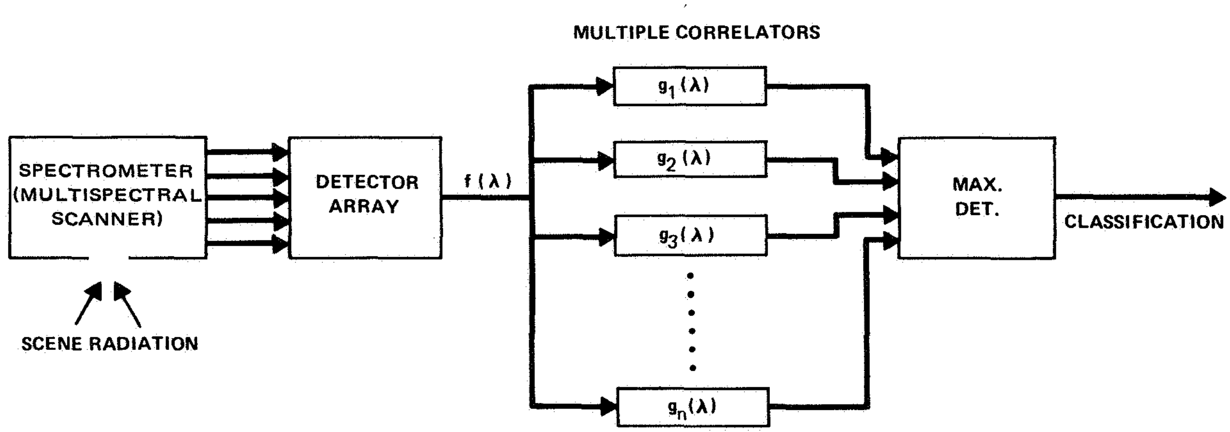

FIGURE 6.3.3 Multispectral scanners and correlators.

Unfortunately, present research indicates that the presence of noise and other contaminants, and the similarity of landscape features and of different crops, may preclude the possibility of a unique identifying mark for each crop, rock, or feature. The classification may have to depend upon the computation of a probability-distribution function of the spectra generated by the measurement of many sample spectra for each output classification required and a maximum likelihood or minimum cost criteria for classifications of each scene or resolution element. Fortunately, a considerable amount of effort has been placed on just such research in the past few years. Numerous techniques have been developed for arriving at classification criteria based upon the (incomplete) knowledge of the probability-density function for specific classes of patterns.

For the case considered, the output from the scanner consists of the detected amplitude at each narrow-frequency band across the range from, say, 0.3- 15 μ. As many as 20-30 such detectors may prove of use, hence the output from the detector array can be considered as a 20-30-dimensional vector. A specific scene or element being viewed then provides the amplitude (coefficient) of each band (frequency term) and the function $f(\lambda)$ can be determined or compared term by term. For the discussion each $f(\lambda)$ thus developed will be considered a pattern (a vector, $\overline{X}_j$, in 20-dimensional space). The patterns $[f(\lambda)]$ belonging to any class, k, (i.e., crop, rock, etc.) are considered as random variables governed by a probability-density function $p(\overline{X}_j/k)$.* If the probability-density function is known, then statistical techniques can be used to derive the optimum** method for assigning $\overline{X}j$ to a particular class. To perform the classification the quantities $p(\overline{X}j/k)p(k)$ for $k = 1, \ldots K$ (each class involved) is computed and $\overline{X}j$ is assigned to that class k_0 corresponding to the largest value of these quantities. ($p(k)$ is the a priori probability that $\overline{X}j$ belongs to class k and is usually a constant that is known or estimated from a sample set of data.) The correlation technique mentioned above is a variation of this procedure where the $p(\overline{X}j/k)$ is replaced by a discriminant function, $g(\lambda)$.

If $p(\overline{X}j/k)$ is known, or can be developed in terms of a few parameters taken from a sample of the patterns in each class, then a discriminant function can be determined which defines a boundary surface between classes of patterns. An unknown pattern is assigned to a region defined by these boundaries by determining the value of the discriminant (see Appendix G.1). If $p(\overline{X}j/k)$ is not known, the nonparametric techniques of pattern recognition can be used to perform the classification (see Appendix G.2) in much the same way.

From the preceding discussion of on-line classification, a system can be envisioned which performs the classification of the output from the multispectral sensor and a system configuration developed as shown in Figure 6.3.4.

The data transmitted provide the user immediately with the information required. The ground-station processor can now use the data directly to generate annotated maps for field use or compute statistics for updating land-use or crop-yield estimates. The data rate has been substantially reduced, and the usable output is made more immediately available to a wider variety of beneficiaries.

The use of this technique need not be restricted to the optical-line-scanners type of sensor but can be considered for processing the outputs from microwave radiometers (Wiley, Autonetics) or panchromatic radar systems (Moore, University of Kansas) as well, providing such outputs are in register from the sensor. This is required to ensure that the response for

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*$p(\overline{X}_j/k)$ is read as the probability of X given class k.

**Optimum is used in the sense mentioned earlier; the probability of classifying a pattern in error is minimized.

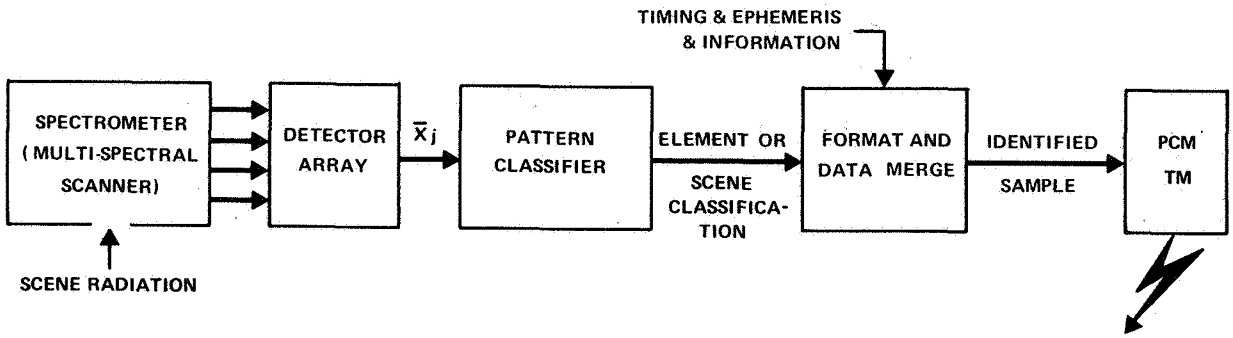

FIGURE 6.3.4 Multispectral scanner and classifier.

each portion of the sensor supplying the information is indeed examining the same scene and resolution element in the scene.

For the multisensor case, a similar procedure can be envisioned. However, here it is more likely that the processing must be done in a ground-based data-processing center, since peripheral equipments will be required to perform the registration, rectification, and resolution compatibility operation.

The idea of examining a scene with high-resolution, color photography complemented by a radar or ir image placed in proper perspective is indeed appealing. However, one sees immediately several conflicts that may arise. The scene as viewed from a camera can be made along the local line of traverse aligned on a vertical axis, the coverage and resolution defined by the film, lens systems, and other components (see Section 2.4). The high-resolution side-looking radar (SLR) normally looks off to the side, the data must be stored prior to generation of the display, and the field of view is a function of beam-width, resolution, vehicle altitude, and other parameters. The coverage of the radar and camera may overlap in part, but discontinuities preclude the immediate merging of the two scenes for automatic processing. Nonetheless, by assigning adequate identification of the frames or frame sequence a user can be provided with multisensor output of similar resolution covering the same region. The registration and orientation problems are accounted for by the user's rather remarkable capability to integrate and absorb these misalignments with a few simple manipulations. However, the process at best is a time-consuming one. When considered in light of weekly or monthly coverage of the earth's surface at 100-ft resolution with a variety of sensors, it becomes apparent that this alternate must be left only to the very dedicated scientist.

The problem is not as difficult if the sensors themselves are compatible, for example, the three-camera TV system as proposed by RCA or the multiple photographic camera system discussed by ITT and GE. Here the sensor irregularities, such as linearity, dynamic range, and other characteristics, can be carefully controlled prior to flight. The output images are of the same type and can be made of the same quality. The linearities in the film or in the photocathode can be recorded and later accounted for. Again, the concept of a real-time automated processing system is not readily envisioned. Each of the frames must be corrected for equipment dissimilarities and a new corrected image or output obtained. This will probably involve computer or optical processing of the raw data. Those nonlinearities that cannot be corrected must be accounted for with computer averaging or by human interpretation.

Consider the use of three TV camera systems of equal resolution. Each system is assumed to be viewing a specified ground area. Filters are provided so that each camera senses only a limited region in the spectral band. To reconstruct a multicolor image from the three images one could telemeter the signals from each camera, receive the signal at a ground station, and reconstruct the image on three similar tubes on the ground. Using wide-range color film, the multicolor image could be obtained from the time exposure of the film as it views each tube, a complicated and time-consuming operation. An alternative to projecting the received signal on a wideband TV system is obviously more tractable; unfortunately such a system is not yet available. Each tube is operating at a different region in the spectral band. Since they are most efficient over a rather narrow spectral band and drop off drastically at other frequencies, a received signal may appear at a different brightness level due to the spectral response characteristics of the tube rather than to its own spectral radiance. Due to the nonuniformities of the tube, a signal of the same intensity will not appear the same at the edges and the center of the tube. Due to sweep nonlinearities, a ground-resolution element on one tube face may not align directly with the same element on the second tube. Normally these deviations and nonlinearities are held to a minimum by good hardware design; but even with a 0.1% nonlinearity in sweep, for example, across 6000 elements, the two merged images could be as much as 12 elements off. With the consideration of 100-ft resolution (100-ft/resolvable element), this implies an order of magnitude degradation in resolution in the multispectral reconstruction. With sweep control and bias introduced on the ground, as well as statistical averaging, this could possibly be substantially improved. Nonetheless it appears that to obtain a three-color image from single cameras one must be ready to face a two-to-four degradation factor in resolution, and a substantial amount of ground processing.*

3.2.2 The Use of Derived Information

Rather than continue the discussion of the problems associated with handling multisensor imagery with the assumption that all frames from all sensors must be identical, the problem of usage of the information will be considered.

In the generation of land-use maps, for example, the user may require that every 100 miles x 100 miles of earth be marked for its actual and perhaps its recommended usage. Provided with a hard copy color transparency of 20-50 ft resolution, an interpreter trained in land-use identification can examine the imagery on a plotting board or light table. He then rapidly marks boundary regions using the plotting equipment provided and notes the classification. The plotting-board markers are fed directly into a computer along with the classification entry, and the acreage for each marked area is computed.

*Some of these disadvantages must be tempered with the consideration of the utility of the TV system, its longevity as a data-sensing system, the ease with which the output signal can be electronically processed, and its usefulness as a single sensor in any of a number of spectral regions.

A master file map or frame is also modified to record these new annotations to maintain it on a current status. In the event the interpreter needs additional information to provide him with the classification, the marking pen is positioned to the region under question. Upon interrogation the multisensor imagery of the same region (marked out by a frame coordinate system) is examined by a classification system designed on each sensor output separately. The output from the classification systems is compared and classification assigned (or probability of a certain classification if there is disagreement) and provided to the interpreter and to the computer. Figure 6. 3. 5 shows an overview of the concept discussed. The intent is to provide an end user with copy (material) in the form most meaningful to him. This is accomplished by allowing trained human observers to utilize the data with the most information (in terms of bits) to do the rapid screening while interfacing with peripheral equipments ready to assist in the difficult discrimination tasks. The registration and resolution problem is alleviated. The interpreter's boundary regions will probably not be defined by single resolution elements (20-100 ft) but will more probably be on the order of 5 or 10 resolution elements (5-10 acres). The resolution of the various sensors need not be the same. The envisioned system contains a separate classification system to handle each sensor output. Each of these classification systems could in turn be simulated on a general-purpose computer. However, the special-purpose system indicated allows for direct input of the sensor output in the most convenient format, eliminates the need for extensive conversion and interface systems, and, with the parallel processing involved, provides a more rapid classification.

To further automate the system discussed, or to provide further assistance to the interpreter in performing his classification task, it may be possible to enhance the imagery prior to his examination. Techniques for edge detection and filtering, smoothing, and image enhancement (see Appendix G. 3) have been used extensively in photointerpretation and are more recently being applied to radar data (Knuckey, CRES, 1966). They have become an integral part of the pattern-recognition technology, and special preprocessing systems and techniques have been developed for specific applications (Viglione, Douglas, 1966; Nillson, S.R.I., 1966; Vanderlugt, University of Michigan, 1965).

Faced with the prospect of acquiring reams of high-resolution imagery covering thousands of square miles of familiar and unfamiliar areas on a routine basis, the data-processing task appears overwhelming. When converted to the numbers of bits and when the amount of tapes of storage required to store this number of bits or the computer time required to process it are estimated the figures seemed staggering. Such a computation, however, has little meaning. What is required is a computation of the information contained in the data, and this must be tempered with the user's requirement, for the information transfer is coupled directly with his ability to use the information made available. The technology is being developed that can convert bits of data to useable information. It can process these many millions of bits now. To assure that when the data become available, the data-processing system is capable of acting as the buffer and providing useable information, giant strides must be taken in these developing technologies. In addition, the users must become aware of these technologies to be able to communicate their requirements in meaningful terms and assist in the development of the logic necessary to extract the required information.

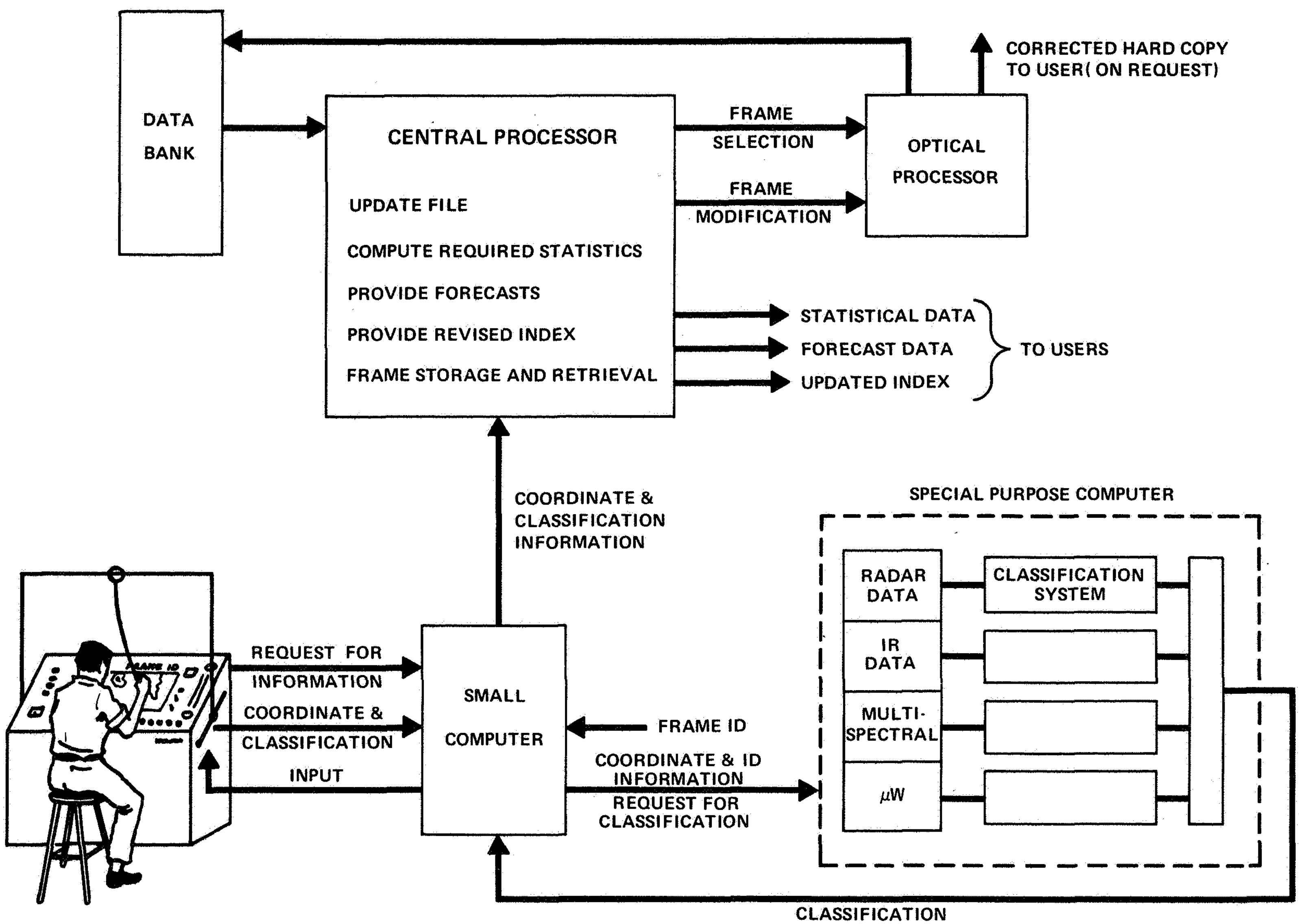

FIGURE 6.3.5 Semiautomated processing facility.

3.3 Recommended Research and Development

Numerous developments must be accomplished or pursued prior to the realization of the type of data-processing systems proposed. Specific areas of R&D will be suggested. The rationale for their need is imbedded in the previous discussions.

With the large volume of data anticipated, a requirement will exist almost immediately for bulk storage media capable of retaining the original fidelity of the imagery and susceptible to frequent retrieval and use. Automatic means must be developed for inserting the appropriate identification on each stored element and for indexing, storage, and retrieval.

With multisensor imagery or for the preparation of mosaics, maps, or stereo views from the same sensor, techniques for handling the problems of registration and the preparation of registered images in compatible format (resolution, color, and dynamic range, for example) must be developed. The conversion of photographic or other spatially oriented high-resolution imagery to digital form for subsequent data processing also requires further investigation.

To assist the user or interpreter in the analysis of the data, equipment and procedures are required to allow the data presentation to be made rapidly in a form suitable for user consumption. Provisions must be made to allow him to interface, in natural written language or in voice communication, with the processing equipment, such that the computer or automatic processing system can provide requested input quickly and reliably upon demand. In addition, image-enhancement techniques, both for reducing bandwidth requirements for satellite-transmitted data and for highlighted features or areas of interest for automatic or human interpretation must be pursued more vigorously.

New hardware is required that will enable the generation of multicolor imagery from several sensors and the generation of high-resolution synthetic-aperture film strips without the requirement for a storage-tube interface.

With the high data rates expected from fine-resolution sensors, wideband telemetry channels must be developed unless methods for on-board data-processing and bandwidth-reduction techniques are evolved, the latter being preferred.

General-purpose computers are already available as flight hardware, but the attendant input-output and software packages must be developed for the computer to be put to meaningful use. Techniques for modifying computer programs or replacing outdated subroutines via telemetry communication bear investigation.

Finally, it appears that the greatest benefit can be derived by an expanded emphasis on automatic data processing. The pattern-recognition technology that has developed over the recent years shows great promise in assisting and supporting the potential user by providing him with meaningful information without the attendant penalty of vast amounts of data. This technology should be vigorously pursued, and in its development some of the related problems of input-output systems, multisensor information processing, and better communication between the processing system and the user will be solved.

APPENDIX A

INFRARED/OPTICAL MECHANICAL SCANNER

Donald Lowe

This appendix presents some simplified relationships useful for preliminary parametric studies of infrared scanners.

Purpose

To map reflected and/or emitted radiance, N_λ, of a scene. User parameters of interest:

ω = angular resolution in steradians,

NETD or ΔT = temperature sensitivity (^oK),

θ = angle of coverage perpendicular to ground track, in radians.

Performance Equation

Thermal Sensitivity:

$$\Delta T = \frac{C \quad f}{A_c \omega E \tau D*} \sqrt{\frac{V/h \; \theta}{\gamma \quad p}},$$

where

C = a constant for a given scene temperature and wavelength region of operation,

f = collector focal length, cm

V/h = spacecraft velocity-to-height ratio,

A_c = area of collector, cm^2

E = optical efficiency,

τ = atmospheric transmission,

$D*$ = detector figure of merit, cm/Watt,

γ = scan duty cycle,

p = number of detecting elements.

Data Rate (number of resolution elements/second):

$$n = \frac{V/h \; \theta}{\omega \quad \gamma}.$$

Typical Performance Capability

$$\Delta T \geq \frac{V/h\ \theta}{4.5 \times 10^5 \omega}$$

for $\omega \sim (1 \text{ mrad})^2$ (a resolution of 1 ft at 1000 ft),

$$\theta = 0.5 \text{ rad} \sim 30^\circ$$

$$V/h = \sim 0.02,$$

$$\Delta T \geq 0.2^\circ C.$$

A scanner of this performance would have a collecting aperture of about 4 in. with a single-element detector.

APPENDIX B

IMAGING SYNTHETIC-APERTURE RADAR

R. K. Moore

Resolution limits for synthetic-aperture systems are, in theory, completely different than for other systems. The transmitter is a major cause of power consumption, although recorder and processor power may be significant. Hence, both resolution and transmitter power formulas are presented here. Some degradation from theoretical performance is of course to be expected.

Symbols used

- F, receiver noise figure
- h, altitude
- ℓ, length of real antenna
- r, azimuth resolution
- R, slant range
- S, signal-to-noise ratio
- V, velocity over the ground
- $W_{T(av)}$, average transmitter output
- W, swath width
- η, antenna-aperture efficiency
- θ, angle with vertical
- λ, wavelength
- σ^o, design value for scattering coefficient

Resolution Limits (theoretical):

Real aperture:

$$r_a \frac{\lambda}{\ell} R = \frac{\lambda h}{\ell \cos \theta}.$$

Unfocused synthetic aperture:

$$r_a = 1/2\sqrt{\lambda R} = 1/2\sqrt{\frac{\lambda h}{\cos \theta}}.$$

Focused synthetic aperture:

$$r_a = \ell/2 \quad \text{(independent of range).}$$

Transmitter Power

Assuming

$W \ll h$, range and azimuth resolutions equal, swath width half theoretical maximum for pulse rate, room temperature for noise calculation

$$W_{T(av)} = \frac{10^{-19} F S h W^2 V}{1.57\eta^2 \quad r\lambda \quad \ell^2 \quad \sigma^o \cos\theta}.$$

Example

Assume

Assume	$F = 2.5$	$W = 40$ km
	$h = 400$ km	$\eta = 0.7$
	$\ell = 8$ m	$\theta = 30^o$
	$S = 10$	$\lambda = 4$ cm
	$v = 8$ km/sec	$\sigma^o = 10^{-2}$

	Focused		Unfocused
	Ideal	20 m	
r	4 m	20 m	70 m
$W_{T(av)}$	225 W	45 W	13 W

Swath-Width Limitation

Swath width is limited by minimum pulse rate and by ambiguity problem.

$$\text{Maximum} \quad W = \frac{3\ell 10^8}{8V \sin\theta}.$$

APPENDIX C

SEMIFOCUSED SYNTHETIC-APERTURE RADARS

R. K. Moore

Customary classification of synthetic-aperture radars is into focused and unfocused systems. Unfocused systems are analogous to lenses focused at infinity, and their resolution is limited to one radar Fresnel zone. Focused systems use the entire period that the object sensed is illuminated by the antenna to build a synthetic aperture yielding a best resolution half the length of the real antenna. As the name implies, focused systems have a specified focal length, but processing the signals permits them to be focused simultaneously at each range of interest. If the antenna on a focused system is tracked so that it continues to point toward the ground element for a time longer than if its look angle were fixed, even finer resolution can theoretically be achieved, but of course such a system could not paint a continuous image.

If all the signal information is stored, no penalty in power is paid for fully focused processing--but storage and processing of all this information can be a problem. With an unfocused system, the signals need only be stored during the time required to build one resolution element, and during this period identity of individual signals can be lost because only their sum needs to be stored. Hence, on-board processing of unfocused synthetic-aperture radars is easy, and a designer would never consider returning the detailed signal histories for later unfocused processing.

Many of the applications in earth-resource studies call for resolutions better than can be achieved with unfocused systems, but much poorer than theoretically possible with a fully focused system. Proposed carriers frequently are not suitable for film return and cannot handle the storage and telemetry bandwidth required for fully focused processing. Thus, an intermediate-type processing is called for. This is called here "semifocused" processing. A semifocused processor can only be useful if it combines some of the simplicity of unfocused processing with some additional resolution enhancement (beam sharpening).

The unfocused processor needs one storage element (integrator) for each range element. The fully focused processor requires storage of each range element for each pulse transmitted during the build-up of an aperture. This can easily amount to several hundred storage elements per range element; hence, the requirement for film or storage tubes. The semifocused processor must use a much smaller number of storage elements than the focused processor but still will require more than the unfocused system. For example, if the resolution of an unfocused system is to be improved by a factor of 2, the semifocused aperture takes twice as long to build as the unfocused, and this time represents four times as many resolution elements. Thus, at any one instant, at least four resolution cells are being accumulated, so four times as many accumulators are required as for the unfocused system. The number of accumulators required is seen to be proportional to the square of the improvement factor.

Various mechanization schemes suggest themselves for such processors --some being suggested by the Doppler point of view and some by the Fresnel-zone point of view. Fortunately, the depth of focus for the semifocused system is greater than for the fully focused system, so, unless very large swath widths are envisioned (this is not very feasible from space for other reasons) a single focusing system can be used for all ranges.

The frequency of the return from a fixed point is Doppler-shifted linearly as the vehicle flies by at constant velocity. Thus, mixing the received signal with a local frequency-modulated oscillator varying in the same way produces a constant-frequency output that can be filtered (or integrated if beaten down to zero frequency). For full focusing, a separate sweep oscillator would be required for each azimuth element being simultaneously processed, along with a separate filter or integrator. With partial focusing, a smaller number of these is required. Thus, for the example in which the resolution is half the unfocused value, only four such oscillators and associated integrators are required.

Looked at from the standpoint of Fresnel zones, the unfocused system uses only the central zone, whereas the semifocused one uses a few of the adjacent zones. Partial focusing can be achieved by storing just enough information for these zones and inverting the zones whose contribution would, without correction, be negative (for a fuller use of this approach, see Moore and Rouse, Electronic Processing for Synthetic-Array Radar, Proc. IEEE, 55, No. 2, February 1967).

Semifocused on-board processors, such as the two examples described, should make it possible to achieve resolutions of the order of 30 m in small-satellite radar systems.

APPENDIX D

INFRARED DETECTOR AND CRYOGENIC TECHNOLOGY IN SPACE

Lloyd Mundie

With downward-looking sensors, a well-defined limit on the detectivity of infrared photon detectors is imposed by noise due to background radiation. Presently available detectors approach this limit to within a factor of 2 or so, but require cooling to increasingly lower temperatures as the wavelength to be sensed increases. Thus, while good performance at 5μ can be achieved at liquid-nitrogen temperature (77°K) using InSb detectors, liquid neon (25°K) is needed to reach 13μ with GeHg, and pumped liquid hydrogen (12°K) is needed to reach 25μ with GeCu detectors. While the limit imposed by noise due to background radiation cannot be exceeded, new detectors have recently been developed which require less cooling than those mentioned above. In particular, the HgCdTe detector presently performs quite well out to 13.5μ at 78°K, and shows promise of further advances in this regard. The spectral response of this material can be varied by changing its composition, and it shows promise of reduced cooling requirements in other regions as well.

The technology of detector-cooling in space has also advanced considerably during the last decade. Short-term cooling can be achieved by liquid transfer. Radiation cooling to liquid-nitrogen temperatures appears possible at least in high orbits; a vigorous R&D program on radiation cooling is strongly recommended. The possibility of combining radiation cooling with such other techniques as thermoelectric or solid sublimation cooling has received relatively little effort, and should be carefully investigated.

Solid cryogens present a useful approach to the cooling problem. Based upon the performance of coolers developed at the Aerojet-General Corporation, it was conservatively estimated* that in order to deliver 15 mW of cooling to a detector at 25°K for a year, a 75- to 90-lb package, 1.5 ft in diameter would be required in an environment at 200°K. With a 300°K environment, the weight was estimated to be 110-125 lb. To provide 12°K, a 2-ft diameter package weighing 137 lb was estimated.

In another study, carried out by Lockheed under a NASA subcontract from Honeywell Radiation Center, it was estimated** that, using a two-stage Ne-methane cooler, 5 mW could be delivered to a detector at 14-16°K for one year in a 200°K environment from a package weighing 29 lb, including the outer vacuum shell. Using solid methane, the same power could be delivered to a detector at 60-70°K, it was estimated, with a package weighing 18-22 lb.

*Private communication with A. Weinstein, the Aerojet-General Corporation.
**Private communication with R. Jansson, Honeywell Radiation Center.

Mechanical coolers employing the Stirling cycle or modifications thereof present an alternative approach to the cooling problem. To date, however, their lifetime has been limited to about 1000 hr due to loss or contamination of the He working medium. Such mechanical coolers have the additional disadvantages of causing some vibration and requiring 30-70 W to operate; this power must not only be provided, but must subsequently be dissipated. The usefulness of such coolers in space thus appears to be limited.

APPENDIX E

COMMENTS ON AIRCRAFT AND SPACE SURVEY SYSTEMS

Amrom H. Katz

E.1 The Case for Aircraft in Earth-Resource Surveys

From the standpoint of science, the earth is, as Wendell Willkie put it, one world. The oceans lap all shores with impartiality paying little heed to political lines drawn on paper maps. The sun shines on all—with differences attributable only to sines, cosines, and the calendar. And the atmosphere affects all, driven by the sun, and responding to the earth surfaces below, but supremely indifferent to political boundaries. As long as man has been on earth, he has responded to and been affected by these vast forces, and he has both used and abused the resources of the earth.

Earth resources have existed for many years. Whether exploited or unexploited, they have not been ignored by consumers, scientists, industry, or bureaucracy. Aircraft, air photos, and the science of using them to map vast areas are not new.

So why the recent and continuing excitement about earth-resources surveys from space? Is it reasonable or proper to regard this idea as heralding the invention of a new subject? Or is it that the advent of a new tool—earth-orbiting satellites—makes possible the accomplishment of tasks not previously possible? Let us look at these questions.

The earth is one, but government agencies have carved it up into separate fiefdoms. Weather belongs to Commerce, trees and crops to Agriculture, and rocks to Interior. There are other assignments. Now, as government agencies go, the U.S. Geological Survey is ancient. It has been using air photos for many years. Though satellites are comparatively new, the possibilities of doing from satellites what is now being discussed were published by the writer about ten years ago. We must look deeper.

Two factors remain. First, but not most important, is the advent of the multisensor business. Aerial photography, with only minor exceptions, has been seeing and portraying what the human eye sees. Because longer-focal-length lenses and/or wider-angle lenses than the eye can be used, and, above all, because photographic film can produce a permanent record for leisurely analysis, photographs have proven very useful. But we are lately, in the post-World War II years, witnessing the introduction of high-resolution radar imagery, infrared imagery, and other sensors that reveal things about the earth, the stuff that grows on it, and the artifacts and patterns introduced by man. These tools "see" what the eye can't see—either through clouds or in darkness. Photography—even aerial photography—is off to a 100-year head start; so it is neither fair nor sensible to compare the well-developed users, analytic techniques, and production base of aerial photography with the experiments, lack of systematic interpretation tools, and shortage of "customers" in these newer arenas of "vision."

The second factor is more important, and we might as well say it straight. NASA, or, more properly, a small section of NASA, in an enthusiastic, imaginative, wide-ranging synthesis, necessitating the expenditure of considerable energy and drive, has made a subject out of these far-flung disparate, fragmented ideas, experiments, and aspirations. Never mind that the task could have and should have been done long ago. They did it, and now is better than later.

On the assumption--made more solid by NASA officials--that the "A" in National Aeronautics and Space Administration (NASA) is not there solely to facilitate pronunciation of the acronym, we should consider the use of aircraft for doing the various jobs subsumed under the title of "earth-resources survey."

There is no requirement here for an extended comparison and discussion of aircraft versus satellites or of the acceptability (in bi- or multilateral cooperative arrangements) of each system.

It should be pointed out that the ground tracks of earth-orbital machines, especially if they are in high-latitude orbits (i.e., near-polar), pass over every country. And if a bilateral arrangement is made with country A, contiguous to or near countries B, C, who might object to being observed, there can and will be unpleasant and nontechnical problems. It is hard to orbit a satellite over only country A. Further, it would seem reasonable that, if we have bilaterals with say only countries A, B, and C, no one will believe that we are seeing data only over A, B, and C. The patently poor economics of so operating only adds to the strain on everyone's credulity. We had better keep political realisms in mind while dealing with the technical aspects of space.

This congeries of problems need not arise with aircraft. As will be shown later, aircraft operation is inexpensive, compared with satellite operation. Even more directly relevant to the discussion immediately above, the aircraft system consists of a group of A/C, any number of which, down to one, can be assigned to any area. Thus, the size of the effort can be tuned to the size of the area proposed to be covered.

There is another important factor which makes aircraft preferable instruments. One of our oft-stated assumptions (or axioms) is that for the United States to engage in a bilateral assistance agreement with country A, that country must do something itself, besides being the (un)grateful recipient of assistance. It should participate as much as possible. Now, suppose we tell A that we have a satellite that will fly over A and deliver data about A. The people of A neither taste, smell, hear, see, nor touch the satellite, before or after launch. The "political participation benefit quotient" for the satellite is close to zero.

If we are going to cover A by an aircraft system, it can be based in A. (To the writer's knowledge, there is no country in the world where we cannot land a 707 type aircraft.) Nationals from A can fly in the aircraft; it can be made the object of press releases and other publicity. This point need not be expounded on here. For aircraft, the "political participation benefit quotient" is measureable and is far greater than that for satellites.

However, the argument will not be settled, nor even made conclusive, without some cost estimates. We turn to that topic.

E. 2 Discussion of a Proposed Aircraft System for Earth-Resources Survey or How to Meet All Requirements with Men in Aircraft (MIA)

In this section we will discuss a system for securing earth-resource data over large areas. We are excluding meteorological coverage. We will exclude systematic coverage of the open oceans, but do not exclude coverage of those waters near shore. (This is deliberately vague and adjustable.)

We assume that, with sufficient R&D, the collection of multichannel imagery in the visible, infrared, and microwave can indeed be used as a high-confidence method of identifying and mapping the desirable quantities that the geologists, geographers, foresters, agriculturists, and urban area analysts have elsewhere specified. We state as an axiom that before these tasks can be accomplished from satellites they can be accomplished from aircraft.

We have been hearing—and we have been shown—some exciting, stimulating examples of what can be seen from Gemini photos. To this observer this comes as no surprise.* As a minor historical note, of little broad interest but of high personal interest, an ancient experience is worth a few words. By 1952, the writer had already spent a dozen years doing and looking at aerial photography from what were then high altitudes of, say, 30,000-40,000 ft. Having heard that the RAND Corporation was studying satellites designed to operate at, say, 200 to 300 miles altitude, the writer decided to prove that nothing useful could be seen from such altitudes. Two very-short-focal-length lenses were obtained, adapted for a Leica, and the writer personally took photographs with the 7.5-mm and 15-mm focal length lenses from a 30,000-ft altitude. Enlargements were a shock, for they showed the streets and bridges of Dayton, Ohio, as well as many other features. For the shorter of the two lenses, the scale number in the vertical is readily calculable to be 1,200,000!

However, despite the exciting photos and the occasionally clever analyses, we have heard no one willing to claim that the state of the art in analysis would now permit worldwide surveys at the ground resolutions of 100-200 ft. These photos would be taken three at a time using different portions of the visible and near infrared spectrum. The tonal variations in these three bands would represent a sort of three-combination safe, which, when unlocked, would permit identification of the contents. We have heard only that more R&D is necessary on this concept. Brock will discuss the meaning of the widely used term "ground resolution" (see Appendix F), so there is no need to expand further. The earlier-cited papers contain discussions of this subject adequate for most purposes.

Discussion with users seems to suggest that what they would really like is a multichannel spectral-response measurement from about 0.4μ to 15μ. This could be provided by a University of Michigan type spot scanner.

Other users, particularly the geologists, find much unique merit in the high-resolution sidelooking radar proposed by Moore.

Many land-use experts are charmed with the results obtained on Kodak Aero Infrared Ektachrome, a color film in which one of the converted layers has been replaced by an infrared-sensitive layer. In developing this film,

*cf. The Space Handbook, published by RAND in 1958 and Observation Satellites—Problems and Prospects, RAND Paper 1707, May 1959, also published in Astronautics, April, June, July, August, September, October, 1960.

the infrared-responsive layer shows up as red. This combination yields interesting images. On the other hand, standard Aero Ektachrome also yields results of much interest.

The way we propose to handle these (nonconflicting) requirements (note that interests have become requirements) is to meet them all. We are proposing, therefore, that in the aircraft collection system to be detailed below we carry the following equipments.

Table of Equipment

1. High-resolution sidelooking radar (characteristics to be supplied separately by Moore)
2. 20-channel spot scanner (0.4μ - 15μ)
   3-mrad resolution (details by Lowe)
   120° coverage
3. Three high-resolution panoramic cameras (detailed description below, filtered to cover the required three spectral bands):
   a. Infrared: 0.7-$.92\mu$ (89B filter)
   b. Panchromatic: 0.6-0.68μ (Pan 25A filter)
   c. Panchromatic: 0.52-0.62μ (Pan 58 filter)
4. Three 6-in. (wide-angle) metric cameras, covering 9 x 9 in. One of these cameras will carry conventional panchromatic film; the second will take photos on Aero Infrared Ektachrome; the third will use standard Aero Ektachrome.

The panoramic will use 70-mm-wide film, cover about 120°, and be fitted with 6-in. lenses. Eighty lines/mm is a realizable and conservative performance figure on high-resolution aerial film. At about 40,000 ft altitude, this yields a swath width of about 30 statute miles. The resolution in the vertical (at the nadir) is given by:

$$\text{Ground Resolution in feet} = \frac{\text{scale}}{300 \times \text{resolution (in lines/mm)}}$$

A 6-in. lens at 40,000 ft yields a scale S = 80,000. Hence,

$$G_{vert} = \frac{80,000}{300 \times 80} = 3.33 \text{ ft } (= 1 \text{ m}).$$

The photography at the edges of the 15-mile-off-vertical position (30-mile swath) is at a slant range of about 80,000 ft. S_x, the scale in the horizontal, in direction of flight, will be about 160,000 and S_y, the scale number perpendicular to the flight line, will be 320,000.

Similar calculations for ground resolution, at the edge of the field, yield:

$$G_x = 6.67 \text{ ft } (=2 \text{ m})$$
$$G_y = 13.33 \text{ ft } (=4 \text{ m})$$

It is appropriate and useful to define a mean ground resolution,

$$\overline{G} = \sqrt{G_x G_y}.$$

In this case, this yields

$$\overline{G} = 9.5 \text{ ft (about 3 m)}.$$

Thus resolution falls off from about 1 m in the vertical to, at the very edge of the field, 15 miles off vertical to about 3 m. It should be noted that these performance numbers meet or exceed every specification and every hope for every job in which resolution is a key factor.

We propose using 70-mm-wide film. We propose calculating our film requirements on the basis that stereo photography will be taken. Now it is not general practice to take stereo photos in two different spectral regions, but it is possible, and with the three proposed cameras we get three viewing combinations: Camera 1 and Camera 2, $C_2 + C_3$, $C_1 + C_3$. Of course, each single camera can produce stereo photos by simply taking two photos of everything, separated by some airbase between photos. This is conventional.

If it turns out that stereo is not desired, or not useful, or not useful enough, this cuts our film load by more than a factor of 2.

To calculate film requirements, observe that the 70-mm-wide film gives a useful field in line of flight of about 2 1/4 in. This, with the 6-in. lens at 40,000-ft altitude, means ground coverage in line of flight of 15,000 ft. To take stereo photos with 60 percent overlap, successive photos are taken every 0.4 of 15,000 ft, or every 6000 ft of aircraft travel. Remember that we proposed covering about 120° across the line of flight. The length of each photo is, therefore, Length = $2/3\pi \times 6$ in. = about 12.5 in.

If we fly a flight line of, say, 3000 statute miles and advance the film every 6000 ft, we will be taking about 2600 photos/sortie, and the film requirements will be much less than 3000 ft/camera. Let us use 3000-ft rolls. Such a roll of film, on thin base, will weigh about 16.5 lb, plus the weight of the spool, totaling less than 20 lb. (We are going to carry this in a big airplane, so this figure is supplied not to comply with a payload budget, but to satisfy the curiosity of the reader.)

So much for the panoramic cameras. The photos produced by panoramic cameras can be used for map revision, and they can be rectified to look like a vertical photograph. For most purposes they need not be rectified, however.

The three metric cameras are conventional 9 x 9 in. format, with 6-in. focal-length lenses. The resolution that could be expected would be about a third to a half as good (meaning twice the numerical values) of that obtained with the panoramic cameras.

These cameras, covering 60,000 ft sq from 40,000-ft altitude, would be used for plotting ground tracks, and the two color-carrying cameras would be useful in checking and comparing integrated color representations against the several separate sensors and films used in the other equipments.

Each of these cameras would carry about 750 ft of 9 1/2-in. film. Now what will all this cost and how much can it do?

We propose considering as an illustrative example, covering all North and South America and Greenland, an area of about 17×10^6 (statute miles)^2, or 12.7×10^6 (nautical miles)^2.

The following analysis is tunable and contains sufficient data on assumptions and operations to enable extrapolation or interpolation for larger or smaller jobs, for more or less frequent coverage.

We will buy a fleet of ten 707 type A/C (or C-135's) equipped as described above, and amortize them over 10 years. We will fly them only 35 hr/month. (Note that commercial airlines would go broke instantly if they used their A/C as little as four times this rate; i. e., if they used their aircraft only 120 hr/month!) Operations and maintenance (O & M) costs for such an A/C include POL (fuel), spares, and maintenance. We will be more than generous in estimating crew size and salaries. The A/C would have to be staged several times during a year, i. e., moved to new operating bases. These costs are estimated.

A truly huge amount of data will be collected on each sortie, and this film must be developed, and the flight lines plotted, before it is turned over to the analysis group. A generous estimate of this cost is made. We will be conservative and allow an active flight line of 3000 miles per sortie, and 5 sorties/month.

The costs can now be tabulated for a buy of ten A/C.

	ANNUAL COST
Ten 707 type A/C @ $\$5 \times 10^6$ each (amortize in 10 years)	$\$ 8.0 \times 10^6$
Ten equipment packages as described above (@ 2×10^6/package)	$\$ 2.0 \times 10^6$
Operation and Maintenance @ \$500/hr Ten A/C x \$500/hr x 35 hr/month x 12 months/year	$\$ 2.1 \times 10^6$
Crew salaries, 10 crews @ 7 men/crew @ \$20,000/year	$\$ 1.4 \times 10^6$
Staging costs for ten A/C, several stages/year	$\$ 1.0 \times 10^6$
Processing and plotting costs @ \$10,000/sortie 50 sorties/month x 12 months = 600 sorties Allow 1/3 failure rate yielding 400 good sorties, and process and plot at $\$10^4$/sortie	$\$ 4.0 \times 10^6$
TOTAL ANNUAL COST	$\$18.5 \times 10^6$

Coverage/sortie of 3000 miles x 30 miles = 9×10^4 miles^2.
400 good sorties/year yield a coverage of 36×10^6 miles^2, or two looks at everything in North and South America.

$$\text{Cost/mile}^2 = \frac{\$18.5 \times 10^6}{36 \times 10^6 \text{ miles}^2} = \$0.51/\text{mile}^2.$$

If the reader, who has been hearing commercial mapping costs of \$2-4/mile^2, wonders how this financial breakthrough has been achieved, let him look at the details. Commercial photography is produced slowly, over small areas, at low altitudes. We have designed a production system.

No direct comparison with a satellite system can be made, because no one dares design a satellite system that will deliver this volume or quality of data.

However, in a subsequent section, we will estimate the cost of a much more modest photographic satellite system, getting resolutions that are not as good by a factor of 5 as the system herein described, and it will be shown that to cover only 80 percent of North and South America will cost at least an order of magnitude more than doing it with A/C.

One final note. It was said earlier that this proposal is tunable—i.e., that to go over some small country, one can peel off one or two of the A/C. To peel off in a quick response to some disaster, whether man-made or nature-made, one can assign an A/C to cover the area at high frequency. This proposal is also tunable, and scalable in another sense. If more or less looks/year are desired, the number of aircraft goes up or down proportionately.

E.3 Discussion of a Hypothetical Photo Satellite System for Land-Use Survey

The following analysis is not rigorous, but heuristic. Whenever possible, assumptions are displayed, permitting and encouraging argument, correction, and verification. In particular, one can scale up or down and see what happens.

We will take, without argument, the requirements as stated by the earth-resources people. They will settle for 100-ft resolution and they want square, single photos showing about 100 miles on a side. They want these photos taken in the by now well-known (but unproven) spectral bands listed below:

BAND 1	0.7-0.92μ, using 89B filter
BAND 2	0.6-0.68μ, using 25A filter
BAND 3	0.52-0.62μ, using 58 filter

These modest requirements can be met with various combinations of resolution obtained in the camera, focal lengths, film size, and altitude. The basic equation connecting ground resolution, G, in feet, altitude H, and focal length F, in the same units and resolution obtained on the film in lines/mm is

$$G = \frac{H}{300RF}.$$

If one assumes R = 50 L/mm, G = 100 ft, H = 125 naut miles, then F = 6-in. is a not unreasonable result.

Using 5-in.-wide film for the image, the coverage of a 6-in. focal-length camera at the assumed altitude will be $\frac{5}{6}$ of the altitude, or just over 100 nautical miles squared.

So far, everything is easy. Now let us launch our three-camera satellite into a near-polar orbit. Assume a 12-16 day life. We intend to recover the photographic film. Why not stay up longer and collect more and more data? Good practice is to avoid the temptation; for, just as a child may not be able to get his hand out of the cookie jar if he grabs too many cookies, reliability factors in delayed recovery may prevent getting anything back. One day's operation is too short and two months' operation is veering toward the cookie-jar syndrome. Two weeks is reasonable. (Note that this is based on one spit-back per satellite. If we could invent an orbital six-shooter (a satellite that fires back film loads at periodic intervals) we could contemplate longer operation. BUT this will cost somewhere in the system.

If the orbital period were an integral submultiple of the day (i.e., if the orbit were exactly 90 min, and 90 min is 1/16 of the day), the satellite ground tracks would repeat themselves, and we would keep covering the same 100-mile swath tomorrow that we covered today. This sad eventuality can be avoided by choosing the orbital height. For circular orbits of height h, a convenient relationship is:

$$\text{orbital period in hours} = 1.41 \left[\frac{R + h}{R}\right]^{3/2},$$

where R is the earth radius.

The assumed altitude of 125 nautical miles avoids this problem. It is left as an exercise for the student to show that it is on a 9-day screw thread, repeating its track every 9 days. Then in 2 weeks, there are available about 1.5 "looks" at whatever it saw.

But the satellite ground swath is 100 miles wide. If the satellite is tuned for the equator, so that it just nicely lays one painted path next to another, without excessive overlap, it will "overkill" in the northern and southern latitudes, for the orbit tracks converge. Conversely, if the path intervals are "right" for the higher latitudes, there will be gaps at the equator. The efficiency of this operation is low.

However, clouds and other obscuration are the curse of this business. Again take, as in the aircraft system proposed earlier, the job of covering North and South America. The cloud statistics over the United States' latitudes (N and S) are not bad, especially when compared with equatorial areas.

Cloud-cover statistics are tricky, and their interpretation even trickier. Does 0.8 cloud cover mean that all the time there is 80% cloud cover, or does it mean that 80% of the time there is 100% cloud cover?

Neglecting these semantic and data problems, it would appear that the chance, over the year, of getting relatively cloud-free photography over this huge area is only about 30%.

Calculations in some DOD studies of somewhat similar and also hypothetical satellites have shown that it would take twelve satellites in a year to get only 80% of the total area—once. How come? Well, the first satellite has the whole of both continents to pick from. The second, third, etc. are busily working on ever-shrinking areas. The series does not converge fast enough—and after twelve satellites, we've still got 20% left to go. It would cost another twelve birds to get 80% of that 20%!

The estimated cost per launch—booster, payload, tracking, command, and recovery functions—can be \$8 million to \$10 million. Taking the middle value of \$9 million, we get an annual cost of about \$100 million—for 80% of 17 million square miles, or

$$\frac{\$10^8}{17 \times 8 \times 10^6 \text{ miles}^2} = \$7.60/\text{mile}^2\text{—for an incomplete job!}$$

Remember the cost for doing this whole area twice with aircraft was about \$0.51/miles^2 or a ratio of 18:1 (satellite costs/aircraft costs).

Remember, too, that we would obtain 20-channel ir coverage, radar coverage, and 3- to 9-ft photos which vary from 30x better to 10x better than obtained from orbit.

E.4 Facing the Analysis Problem

It is one thing for a briefer to project a few Gemini photos and then expound at length on what can be seen. It is quite another to contemplate what will happen when the floodgates are opened and new data pour from the sky.

The analysis and data-handling problem is always downplayed, ignored, and underestimated. Let us see why. Most answer-acquiring systems can be subdivided into four subsystems--airborne data collection, physical data processing, analysis, and presentation and dissemination.

Now, were ink density on each of these rows proportional to the attention, interest, dollars, priority, ..., to sum it up, scientific/technical/administrative appeal, the distribution would look something like that in Figure 6.E.1.

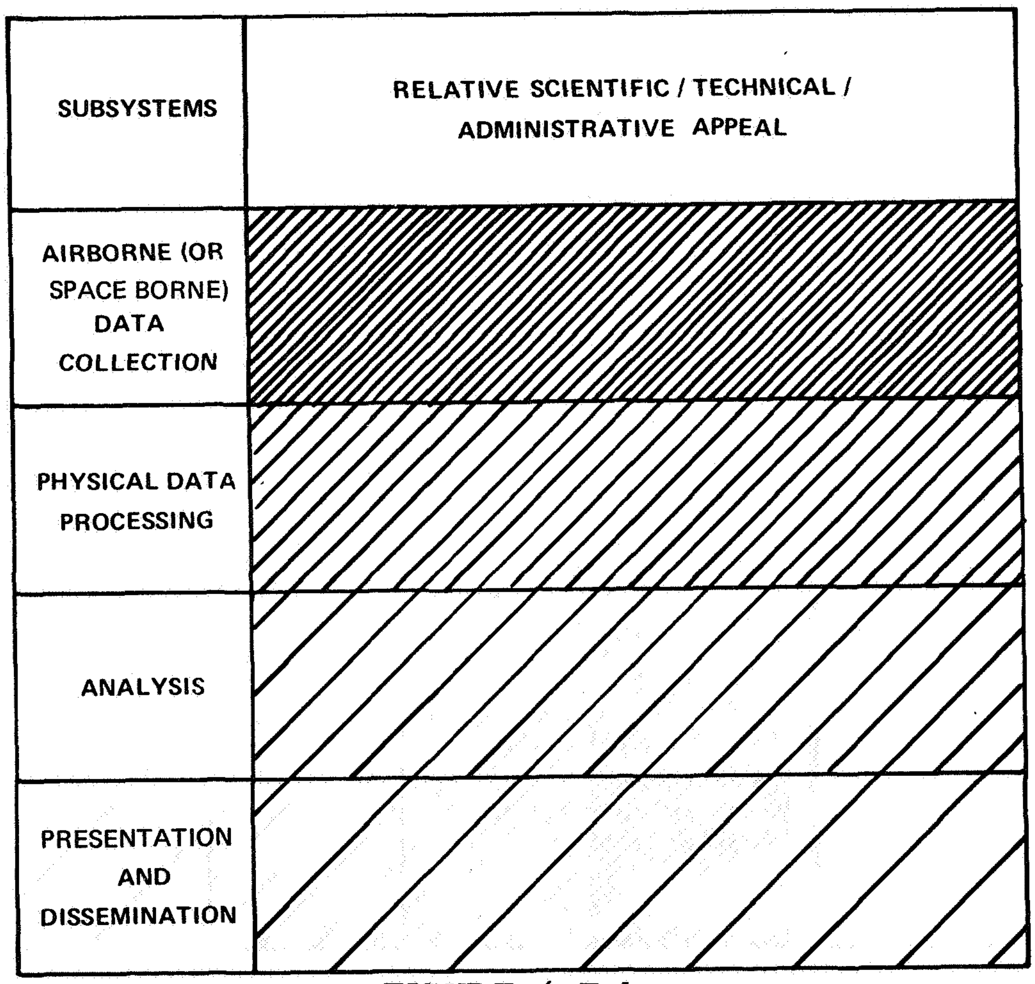

FIGURE 6.E.1

Most of the effort, as measured by priority, attention, interest, and dollars, goes into the glamour stock, the collection subsystem. And the successive subsystems get increasingly less effort.

To say briefly what deserves lengthy discussion, photointerpreters can aspire to the rank of major, but pilots can become generals. In other words, the action (and the money) is where the data are collected.

Were this same answer-acquiring system subdivided in the other direction, one finds that most such systems can be broken into four components—hardware, techniques, people, and organization. By "people" we mean the training and hiring and firing of the personnel in the system. By "organization" we mean the wiring diagram relationship between this system and other organizations, such as consumers and R&D labs.

Varying our tonal quality again, and coloring these four columns proportionately to the effort applied, we find (see Figure 6. E. 2) a distribution similar to the first one, but at right angles.

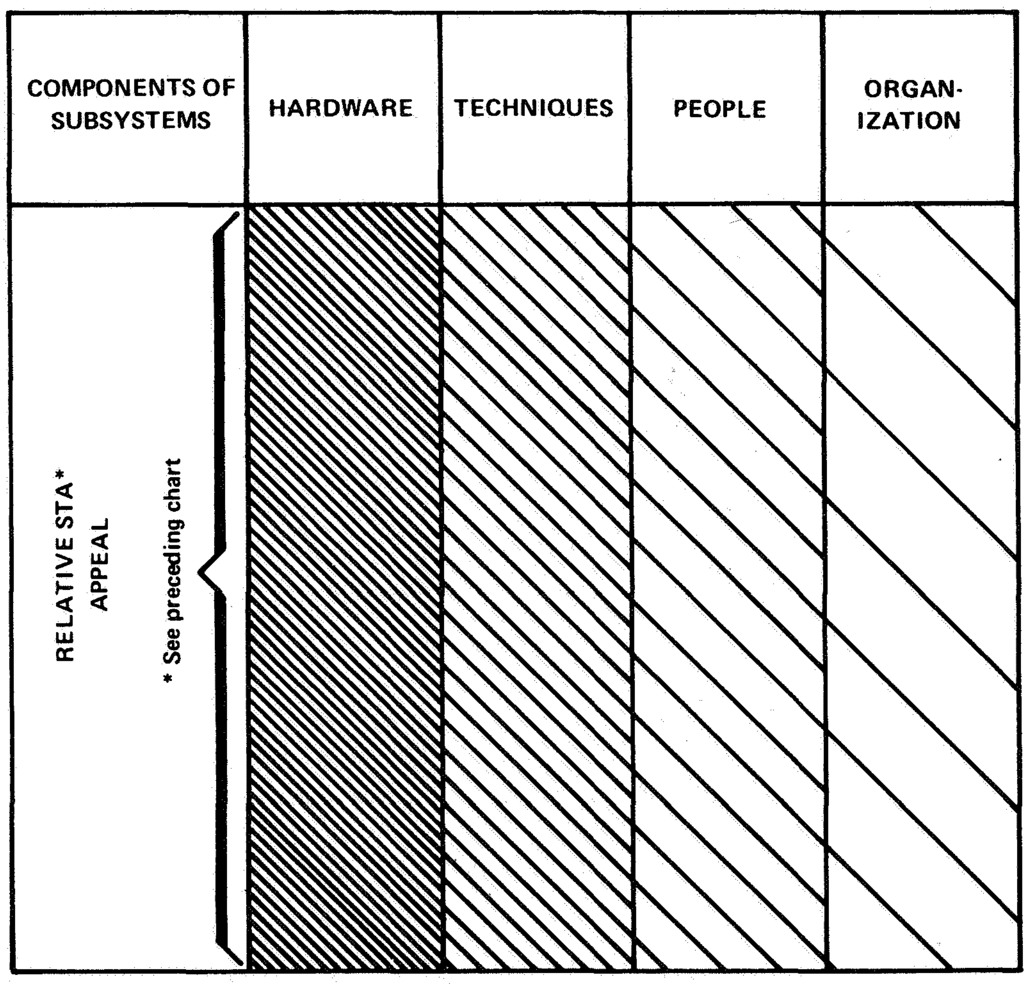

FIGURE 6. E. 2

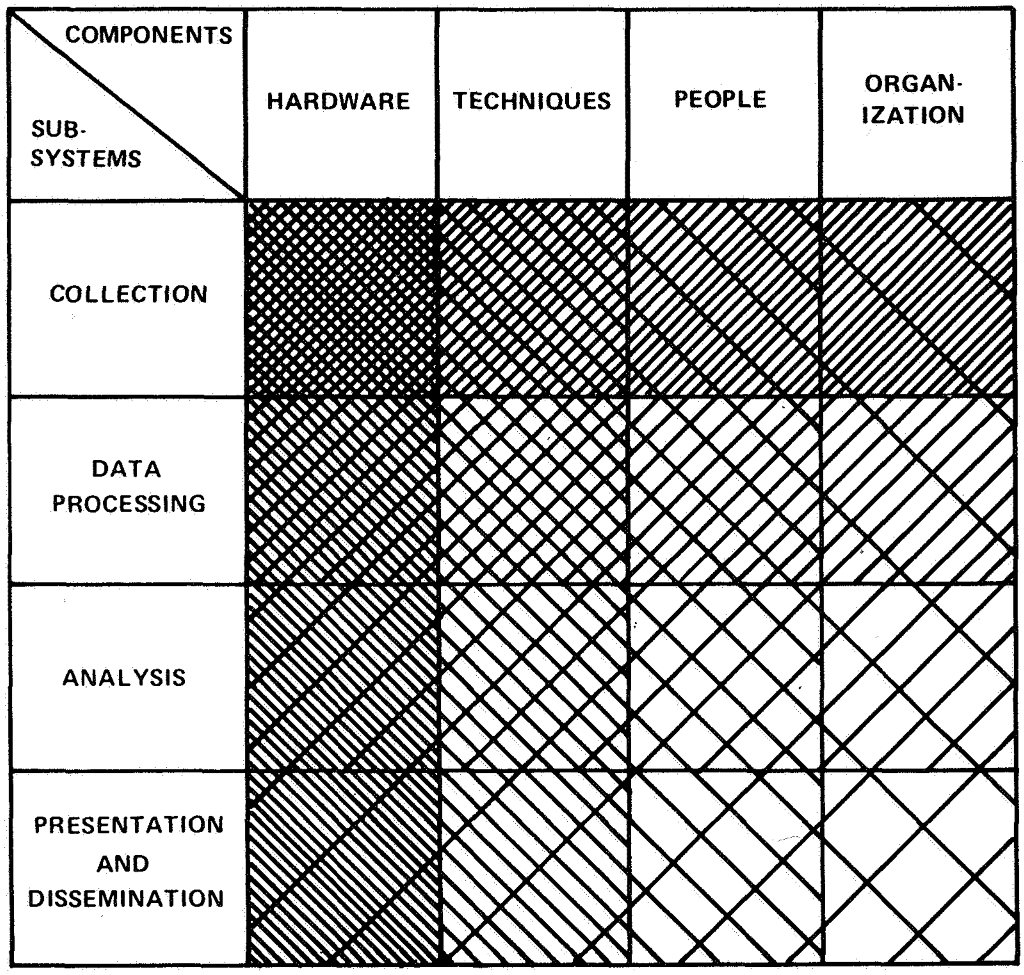

FIGURE 6. E. 3

Combining these two charts we get Figure 6. E. 3. Everything piles up in the northwest corner--collection hardware!

Analysis, to pick one of the softer, if critical, pieces of the pie, gets short shrift.

This can be avoided only by paying much more, and early, attention to this problem. Later in this paper we will develop cost estimates for doing global, or near-global, surveys properly. Neither science, industry, nor the taxpayers will long stand the notion of hundreds of millions of dollars being accelerated up off the launch pad, but with little beneficial results trickling down.

Take our previously used example of North and South America, which is about 1/3 the land area of the world. Consider the numerous questions already raised (and adding those likely to be raised after data are in hand) about distribution of crops, yields, forest lands, transportation, and urban patterns, and many more phenomèna and the varied forms in which both partial and completed data will be stored, presented, and used.

When we realize that multisensor imagery and nonimagery data will be collected, that it will have to be filed, plotted, duplicated, enlarged, reduced, combined, that mosaics may be made, maps produced, both true and false color prints made, specialized atlases and encyclopedias published (to lift the lid only slighly on our Pandora's box) we can discern the magnitude of the required efforts.

Let us proceed to estimate the cost of analysis. We assume that coverage of the area will be obtained several times per year, and there will be some number of special smaller areas requiring special study and more frequent or more concentrated coverage.

Our analysis center will have imagery interpreters, specialists in photo, radar, and infrared interpretation. To paraphrase the title description of Sir Thomas More, we will need not only men who are interpreters for all seasons, but interpreters for all wavelengths. Some will be area specialists, others will cut at right angles and be functional specialists. (Example: We might have a man specializing on West Boondakistan and another man specializing in railroads. Their interests intersect and overlap but clearly are different.)

There will be specialized viewers and projection apparatus, measuring instruments of various sorts, automatic isodensitometers, and recording microdensitometers. We will need darkrooms, photo labs, and mass print and transparency production facilities, for both black and white film as well as for color film and products. We will need library and filing facilities, with retrieval of various types of data. Computers and their human assistants will be needed, in quantity.

This description only scratches the surface. Besides what is in the building, we will require communication equipment and people--to direct, question, and intersect with ground-truth teams checking specific items in field locations.

Printing and publishing facilities will likely be required--for putting in useful form the varied outputs of the analysis center.

Well, what size operation are we talking about? Organizations somewhat similar but not identical to the one herein postulated, exist--reconnaissance technical squadrons (RTS), the Army Map Service (AMS), and the Aeronautical Chart and Information Center (ACIC). Although somewhat disconcerting at first sight, further reflection and analysis makes not unreasonable the observation that for each (photo) interpreter, there are about ten men behind him--laboratory technicians, plotters, printers, librarians, computers, typists, editors, and the like. We have not even mentioned administrative overhead, that component of all organizations which incurs obvious and visible costs without producing clear or tangible benefits.

Now in our building, concerned as we will be with as many subjects, wavelengths, and special topics, and above all, huge areas, it is unlikely that we can get by with only 25 interpreters; it is painful to believe and hence unlikely that we will need as many as 2500. Let us take the geometric mean, and call for 250. This is not unreasonable. Using the 10:1 backup figure produces an estimate of 2500 people.

A conservative estimate for the cost of the building, fully equipped, would be about $15-20 million. Annual operating cost (for the 2500 people) would be about $50 million.

We do not--and would not dare--propose to start full-bore. A starter set for such an operation would be about 500 people--1/5 full-scale.

We are talking about using, on a production-line basis, uncommon skills or skills not yet in existence. There are few radar-imagery interpreters, as applied against nonmilitary objects and subjects such as geology and crops. Despite almost 20 years of fooling with and flying infrared imagery-producing apparatus, there are pitiably few interpreters of this material, and again, still fewer who have paid attention to the nonmilitary fields. The ability to analyze, code, and decode the output from a multichannel recording spectrometer is still rarer than the other skills.

All this argues strongly for starting the analysis center at small scale, learning, teaching, developing skills, and then expanding.

Previous papers by the writer indicate that cost estimates for securing data over North and South America using aircraft and satellites were as follows:

Cost for covering North and South America twice/year with an aircraft system	$\$18.5 \times 10^6$
Cost for covering 80% of North and South America once with a three-camera photo satellite system	$\$100 \times 10^6$

The superficial and first look at these two numbers develops a ratio of about 7:1 in costs. But the aircraft system did 36×10^6 miles^2 and the satellite system did but 80% of 17×10^6 miles^2. The ratio of \$/mile^2 is now about 18:1. Neither of the two sample (and simple) calculations above included analysis costs. If we assume annual costs of $\$50 \times 10^6$ for analysis, and add this in, we get:

$$\frac{\text{Cost of 1 year satellite operation}}{\text{Cost of 1 year aircraft operation}} = \frac{100 + 50}{18.5 + 50}$$

$$= \frac{150}{68}$$

$$= 2.2 \text{ to } 1$$

To sum up, analysis, i.e., getting and presenting usable, timely answers, is usually disregarded, left to chance, assumed, or underestimated. We do not need or want one more sad example to cast on the stockpile of history. If mistakes are to be made, let them be new ones. Making a new mistake is regrettable, but making old ones is stupid.

E.5 What's A Good Bet?

A good bet for application of a new technique--such as measuring, exploring, studying, or mapping earth resources from data secured by spaceborne sensors--usually requires that the realizable benefits exceed the cost of securing the benefits.

The "usually" in the preceding statement is not deployed frivolously, because some tasks need doing based on extrinsic and further considerations, in which accomplishment of the particular task at hand is necessary to spark or catalyze other developments and thus act as a multiplier.

Further, given a series of situations--or countries--in varying states of development, one might develop a weighting system (confessedly simple-minded) that reflects the absolute value of the operation (e. g., the GNP of the country) and the ease with which improvements can be made by the proposed system.

The first of these two factors merely argues the obvious: that, all other things being equal (which they seldom are), a fixed percentage of a big amount is larger than the same percentage of a small amount.

The second factor is simply the marginal utility. If a country is well mapped, well explored, well inventoried, well reported, well . . ., it is unlikely that an additional tool, such as afforded by space sensing gear, will make as much difference as it would in another country, less developed, less . . . --if in the second country there are ways and people ready to use the information on a taut leash, ready to go. Despite the protestations of the various specialists, the United States, to take a country at hand, is well developed, well mapped, ... Certainly this is true by comparison with what are called "less-developed countries" (LDC's). It might be argued that the marginal ability of spacecraft sensors is lower when used over the United States than when used over some LDC.

Even if this conservative assumption is so (and taking India as an example of an LDC, one is hard put to believe, let alone argue, that in the foreseeable future India could better exploit resource surveys than could the United States), the economic multiplier of the United States is so huge that one will almost always come up with weighting factors that give the United States highest priority.

This result is not uncongenial. For a long time the equivocality of space-derived data and its interpretation will require that much ground truth be obtained to check and supplement space-derived data. Much experimentation will be needed before making international commitments of whatever variety. (This suggests that we hold our tongue, internationally, and not force a country into the role of Tantalus by our holding out benefits that we can't deliver.)

We will have to shake the system down, debug it, and probably engage in noneconomic operations--for a while. The United States can better afford noneconomic operations--where cost exceeds benefit--than can anyone else.

E. 6 The Limiting Case

The biggest and "worst" problem area outside the United States (subject to the constraint that the United States has an active interest in helping this country and this country is "willing" to be helped) is India.

Let us imagine the most favorable outcome of the earth-resources satellite program. We have run the program, and it has worked. All desirable and needed data have been secured, reduced, analyzed, and put in usable form. Maps, land-use patterns, hydrologic, geologic, demographic data are all available, as are any data that one can conceive of wanting or using.

Let us further suppose that we have an Indian Data, Information, and Analysis Center (IDIAC), that the data are kept up to date, and that they are readily accessible and available in map, graphical, digital, or any other form.

What can we (or India) do that will be significantly different than could be done in the absence of more data than now exist? How could such a cornucopia of data be used? Will it make a difference?

Are these data genuinely important, or will their importance and impact be far overshadowed and outweighed--if not vitiated by national habits, customs, mores, institutional problems, religious factors, and ineptitudes of various sorts.

These questions are raised not to prevent programs from getting off the ground, but to make sure the expectations are not raised unduly, and that the narrow perspective forced by technological blinders does not obstruct the full field of problems.

These questions are, of course, part of a broader series of questions. Can we expect India to take advice? Can we design and erect cooperative bilateral training centers? What does our cumulative experience with India to date suggest?

Or, more directly, do we even understand the process of foreign aid to LDC's based on happy--but mainly irrelevant--models drawn from Western-sophisticated, Marshall Plan countries?

Going to the limits, as in this example, can help clarify the assumption and moderate expectations, and illuminate otherwise dark corners, and help chart a smooth passage.

This is not a plea for scientists to stop working on scientific problems and start working a sociopolitical problem any more than it is the reverse. But if there is to be mutual benefit, the efforts on these two axes should not be at right angles--or there will be no cross-product.

Scientists, engineers, and technologists working in or on space are immersed in and concerned with a physical vacuum. They must avoid working in a political vacuum as well.

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NOTE: Attention of the reader is invited to Appendix H, which comments on this paper.

APPENDIX F

RESOLUTION AND MICROIMAGE QUALITY IN PHOTOGRAPHIC AND OTHER SYSTEMS

G. C. Brock

F. 1 Introduction: Definition of Resolving Power

Imaging systems for observation from space platforms are often compared in terms of their resolution; i. e., a system is said to resolve so many feet on the ground from its operating altitude. The exact meaning of such statements is rarely given. This does not matter much when comparing systems of widely different resolution; e. g., a 10-ft photographic system with a 500-ft television system, but when the competitive systems are not orders apart it is desirable to know just what is meant by the word "resolution" in each case. The purpose of this note is to clarify the meaning of resolution for photographic systems and to discuss various other factors that bear on microimage quality but may not be generally appreciated.

Resolution expressed as feet on the ground is derived from resolution in the image plane by multiplying by the appropriate scale factor. Katz gives the useful approximate formula

ground resolution (feet) = scale number/300 R,

where R is resolution in lines per millimeter and the scale number is the ratio of the altitude to the focal length. Thus a 12-in. lens at 500,000 ft and a system resolution of 100 lines per mm gives

$$G = 500,000 / 300 \times 100 = 17 \text{ ft.}$$

F. 2 Measurement of Resolving Power

Resolving power is measured by photographing some standard target array containing a multiple bar pattern repeated at a range of sizes. In the USAF target (Figure 6. F. 1), the basic unit is a group of three bars, the bar length being five times its width and the separation being equal to the bar width. The dimensions change from one unit to the next by a factor of $\sqrt[6]{2}$. The photographic image is examined under optimum magnification (typically about 0. 6 times the resolution in lines per millimeter) and the resolving power is determined from the nominal image dimensions of the smallest unit in which the triple pattern can be distinguished. If the nominal width of the bars at image scale is w, the resolving power is 1/2w, i. e., a "line" is a bar plus a space. This differs from television practice, in which

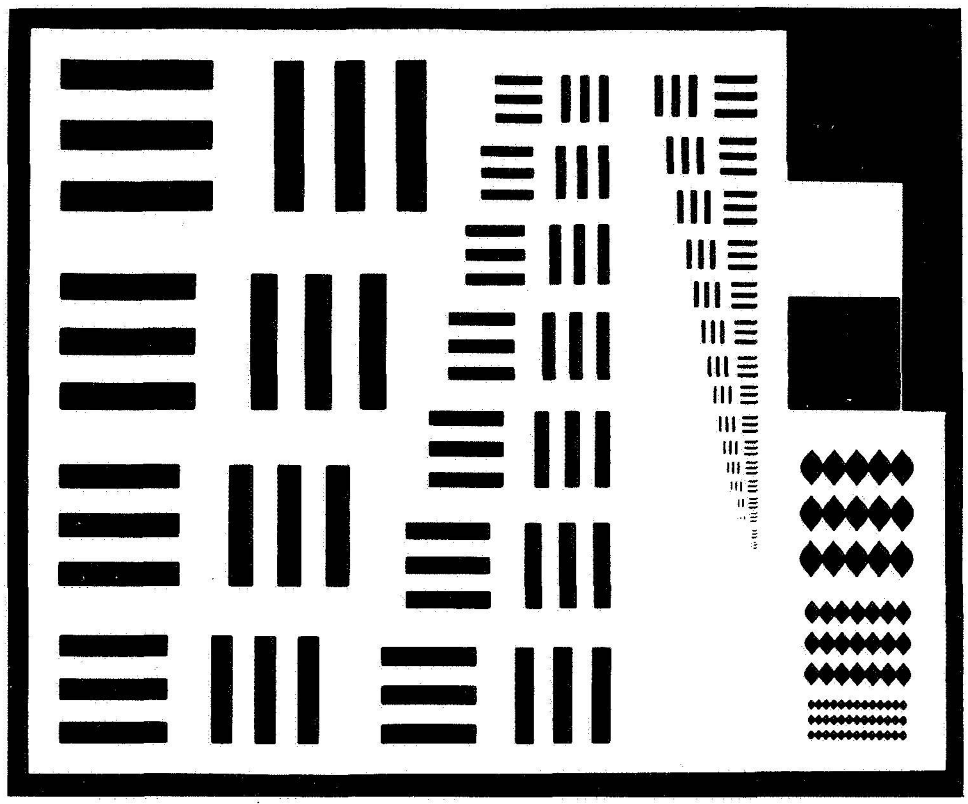

FIGURE 6.F.1 USAF three-bar target.

the lines nearly touch and all lines are counted. Although photographic and TV systems cannot be compared on an exactly equivalent basis by resolution, it is usual to consider that a resolution expressed in photographic lines per mm corresponds to twice that number of TV lines; thus a ground resolution of 100 ft TV corresponds to 200 ft photographic.

More recently, photographic resolutions have been expressed as cycles per mm, but neither lines nor cycles are quite appropriate. The bars are too wide to be called lines, and the pattern does not contain enough repeats (its Fourier spectrum is far from pure) to use cycles.

In general, a photographic-resolving-power test involves an imaging device, such as a lens, and a receptor/detector, such as a film. Since the result depends on the properties of both lens and film, we cannot properly speak of the resolving power of either lens or film by itself. However, for system design some such assumption is often necessary, and it is customary to quote film-resolving powers determined with a lens that imposes a negligible limitation on the film. Lens-resolving powers are sometimes measured by observing the aerial image with a microscope. This enables approximate predictions of overall lens-film-resolving power to be made, but the visual resolving power of a lens can be quite misleading as a guide to its general quality. Nowadays better analyses of performance can be made using the modulation-transfer function. It should be appreciated that the published figures for limiting resolution of emulsions are determined with very high-grade lenses such as microscope objectives, and the figures obtained in practical aerial cameras will be much lower.

F. 3 Nature of Resolving Power

The resolving power of a system for a particular target represents the limit of a progressive deterioration in image quality that sets in at much larger image sizes. In a typical case, if the resolution limit is at 100 lines per mm, the image contrast falls to half its macro value at about 30 lines per mm. The rate of fall of contrast depends on the target; thus it is less rapid for sharp-edged periodic targets such as three-bar targets than for periodic targets with sinusoidal intensity profiles. The most significant difference, however, is between periodic or quasi-periodic targets, such as tribars, and isolated single bars; the latter lose contrast relatively slowly. This phenomenon may be observed in aerial photographs, which often show isolated line details whose nominal width is far below the resolution limit.

These and similar phenomena are studied nowadays with the aid of the modulation-transfer function(MTF) of the lens and film, together with film granularity and H and D curve. The MTF is defined as the Fourier transform of the spread function, which is equivalent to the spatial frequency response of the system for sinusoidal targets. The granularity expresses the random density fluctuation when the uniformly exposed film is scanned with a small aperture. Given the lens and film MTF's and the H and D curve, the contrast and shape of the image can be calculated for any target at any image size using Fourier transform programs. The granularity represents a random density fluctuation or noise level, which effectively increases with spatial frequency, since pictures are looked at with magnification inversely proportional to image size.

Applying these methods to typical systems, the modulation of density across the target image at the resolution limit is found to be approximately equal to the granularity calculated for an aperture having the area of one bar of the target. Thus the signal-to-noise ratio is on the order of one.

In general, a resolving-power limit is the spatial frequency at which the product of the target modulation (contrast), MTF's of lens and film, and the film gamma yields a visually just-detectable modulation in the image. In typical systems the image looks grainy at the resolution limit when viewed under optimum magnification, and the performance is limited about equally by lens and film. If the performance is limited solely by the lens, the images will not look grainy; conversely, if solely film-limited, they will look very grainy.

The observed resolving power is finally determined by the observer's ability to see (or convince himself that he can see) the triple pattern of the target, partially broken up by the noisy background. It should be particularly noted that the just-resolved image resembles the target only in its possession of three separable elements; the shape is different and grain breaks up the continuity of the bars. Observers differ in their reaction to any given resolution situation, and, although rules for reading are often drawn up, it is fundamentally impossible to make unambiguous rules. Also, one observer will react differently on different days. The writer has pointed out elsewhere that Martians would not necessarily agree with our resolution readings, though they could not produce different MTF or granularity figures. Apart from the purely subjective effects, the signal-to-noise situation imposes a statistical uncertainty on the resolution limit. In general, the resolving power of a photographic system should be given as the average of a large number of replications and preferably with statistical limits. Any individual observation may differ from the mean by, say, + 20%. Given ten or more replications, the confidence limits of the mean can be set within, say, + 5%. If in practice it is required to use a system at the actual resolution limit, it should be realized that the quoted figure will be subject to the kind of statistical fluctuation just quoted. Usually, of course, detail is interpreted at sizes well above the resolution limit.

If grain is an insignificant factor in resolution, the limit is determined by the ability of the eye to detect a small density variation across a quasi-sinusoidal image, and the precision is better. Conversely, if the system is grain-limited, the disagreement about the limit of resolution tends to be worse. In practice, because of other constraints that enter into system design, useful systems tend not to depart very far from the typical situation in which grain and MTF both play a part in limiting the performance. Nevertheless, it is useful to be aware of the extreme cases, in order to emphasize the limitations of resolution (or any one-number criterion) as a description of image quality. If in just-resolved images we have in one case a smooth density variation, and in another case a conglomeration of grain clumps that can be imagined to join in a triple pattern not much bigger than the clumps, the two images are obviously different in kind, whatever the equal resolution numbers may say. Much more information is needed about the significance of such differences for information storage, but there is good evidence that the grain-limited system is undesirable for aerial photography because of inferior reproduction of low-contrast detail. (This is another way of expressing what Katz calls "Goddard's Law.") Unfortunately, the trade-offs in emulsion speed and granularity seem to be pushing system development toward the grain-limited, very-high-optical-performance cameras.

F. 4 The Effect of Contrast and Other Factors on Resolving Power

The resolving power obtained in practice with any specific lens/film system depends on numerous factors. Some of these are concerned with the optical image, e.g., focus errors, field position, and residual error in image-motion compensation. Knowledge of these and how to deal with them is part of system design. Others relate to the use of the film, e.g., resolving power can be significantly affected by exposure level, developer composition, and mode of application. Operation within restricted light limits and standardized processing techniques are necessary to cope with such effects and are part of good operating practice.

More fundamentally, resolution also depends on the type of target, thus higher values would be obtained using a three-bar target with longer bars, lower values if the rectangular bar profile were replaced by a sinusoidal profile. The essential point to stress here is that a resolving-power figure sorts systems out into a relative order of performance which hopefully is the same order that will obtain in practice; they do not predict what detail of some unspecified shape can be detected or what tasks can be performed with a particular system. Rough empirical rules showing a relation between resolution and recognition may be devised, but in general the need for a given resolution level must be based on experience.

By far the most important factor affecting resolution or detection is the contrast of the target. The relationship between contrast and resolution is quite complex, as it depends on the MTF, granularity, and gamma of the system. As an example we may consider the limiting case of film used with an essentially perfect lens, hence the effective MTF is that of the film, and for this purpose all film MTF's may be considered to have the same shape. Figure 6.F.2 shows how the resolving power of three emulsions varies when target images of various contrasts are projected upon them. Such curves are sometimes called "thresholds" because they indicate minimum contrast required for resolution as a function of frequency; hence when a lens MTF is drawn on the same graph the intersection gives the resolving power to be expected from the lens-film combination. The threshold includes the overall effects of the target contrast, emulsion MTF, gamma, and granularity, plus the characteristics of the human observer. The main part of the threshold is the approximately linear portion at a slope of 45 deg; this is determined by the granularity limit on the visibility of detail. A full threshold would include a horizontal portion at very low modulation, defining the region in which grain is negligible and resolution is determined mainly by gamma and the contrast sensitivity of the eye. This area is difficult to measure but is not of major importance and is not shown.

Figure 6.F.2 shows that the limiting high-contrast resolution for 4404 emulsion is in the region of 800 cycles per mm, but if the contrast is dropped to a modulation of 0.06 (1.1 to 1.) the resolution is only 80 cycles per mm. In general, the contrasts in aerial scenes are low. When looking vertically through the whole atmosphere the apparent contrast for black and white objects does not exceed about 6 to 1, and the typical contrast for adjacent small details is 1.2 to 1.0. These very low-contrast values, and the critical dependence of resolution on contrast, indicate the need for imaging systems that maintain contrast down to the smallest possible size. In general, the MTF's of optical systems vary more in shape than the MTF's of films, and the MTF's giving highest resolution do not always give the best contrast at larger sizes. Whereever in system design there is a choice between maximizing the ultimate resolution and maintaining good contrast transfer at larger sizes, careful consideration should be given to the latter. The point is elaborated in the next section, but here we may point out that a change of spectral band can often be very effective in achieving resolution. Consider the image of, say, water in a grass background. In broad-band panchromatic this could have some very low contrast, say 1.05 to 1.0, which is well below the contrast needed for resolution on 3404 film at 150 lines per mm. To resolve this detail it would be necessary to improve the MTF by a factor of 2.5 or increase the scale by the same amount without lowering the MTF. The same result could be achieved at far less cost by using near ir, which would easily raise the contrast by a factor of 4 or more. In some circumstances a double camera using two spectral bands could be more useful than one camera of much higher resolution.

F.5 Resolution versus Micro Contrast

As previously stated, the quality of definition in an optical system starts to deteriorate at sizes much larger than the resolution limit. In Fourier terms, the spatial frequency spectrum of the target is reproduced through an MTF which falls progressively from zero frequency upwards; the MTF is never flat, as the frequency response is often flat in electronic systems. Insofar as there is any choice during system design, by aiming at one MTF shape rather than another, the question is how to weight the relative

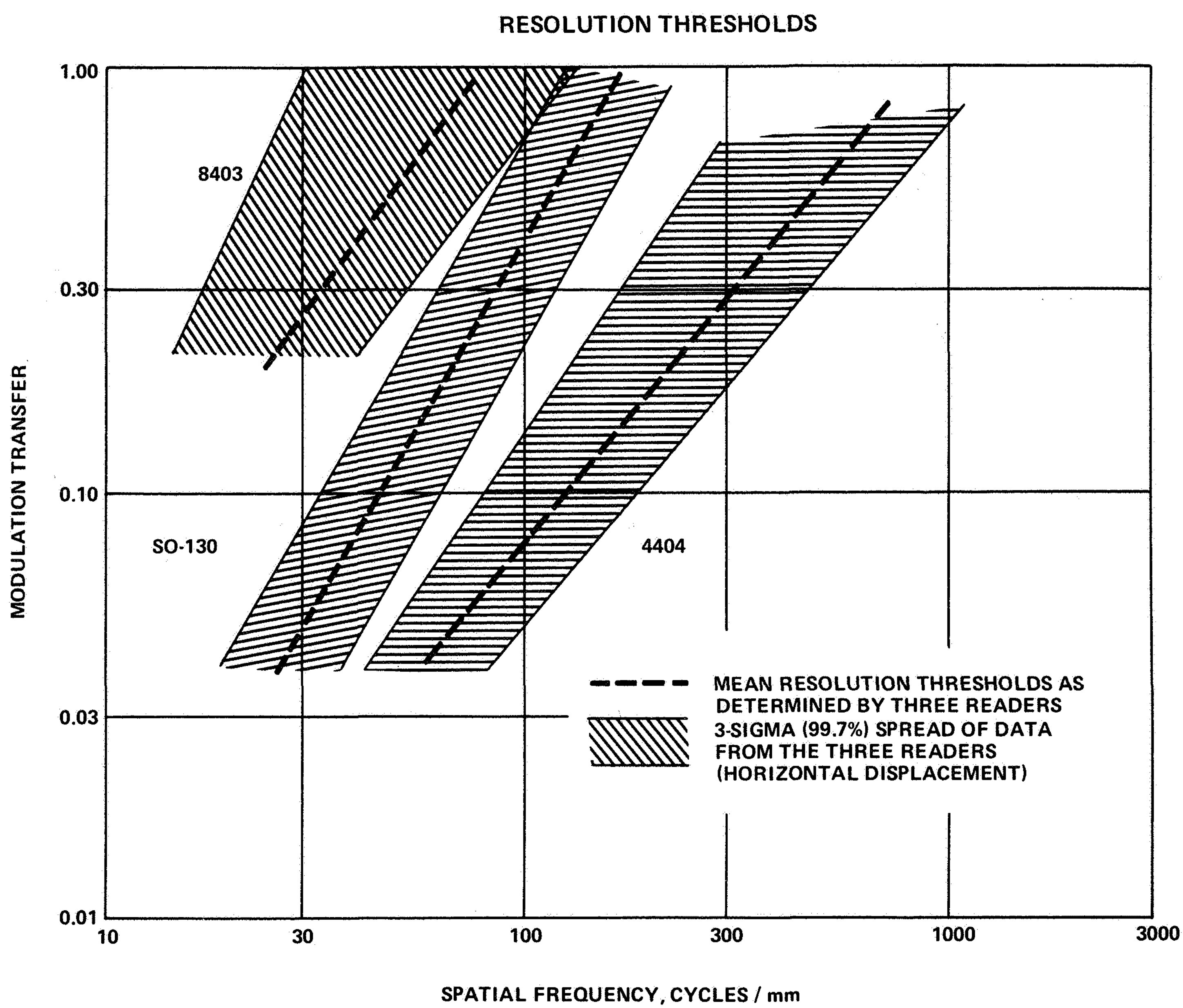
RESOLUTION THRESHOLDS
MODULATION TRANSFER
1.00
0.30
0.10
0.03
0.01
10
30
100
300
1000
3000
8403
SO-130
4404
MEAN RESOLUTION THRESHOLDS AS DETERMINED BY THREE READERS
3-SIGMA (99.7%) SPREAD OF DATA FROM THE THREE READERS (HORIZONTAL DISPLACEMENT)
SPATIAL FREQUENCY, CYCLES / mm

FIGURE 6.F.2

advantages of response at high and low frequencies, respectively. "High" and "low" are relative terms, and for the present purpose high will be assumed to mean "near the resolution" limit for high-contrast targets, while "low" is on the order of one quarter of this frequency. As a rough indication, the high-contrast limit is found at a value of 5 to 10 percent on the MTF.

In practice, flexibility in MTF shape is only available in the lens--one has to assume that the film manufacturer always does the best possible at a given speed and granularity.

The relative importance of high and low frequencies naturally depends on the size and frequency spectra of the objects to be recorded. At first sight it might appear that higher frequencies are more important for smaller objects, but this is only partially true. Certainly a periodic object with very small spacing contains a large percentage of high frequency, but such objects are not common. A small isolated object is a wide bandwidth rather than a high frequency. Its perfect reproduction admittedly requires high frequencies, but reproduction is never going to be perfect, and the high-frequency content is a small fraction of the total energy in the bandwidth. Remembering that the higher the frequency the lower the reproduced modulation, it is not obvious that concentration on high frequency at the expense of low is desirable. Broadly speaking, high frequencies determine shape, whereas low frequencies determine contrast against the background. Contrast in aerial scenes is very low indeed for the vast majority of small details. Exceptions are certainly encountered, e.g., light streets or buildings, but the very fact that they are light means that they will take care of themselves, within reason, however small they may be. For the majority of details it may be better to sacrifice bandwidth in the MTF for the sake of higher response at low frequencies, which will improve the signal-to-noise ratio of the basic pulse that makes the object visible. Perhaps there is no point in passing high frequencies in the hope that they will improve shape rendition if their recorded modulation falls near or in the noise level. In short, imagery anywhere near the resolution limit inevitably involves compromises. This is a complex question which cannot have a general answer. Its solution can only be approached using actual numbers, i.e., knowing what size objects are to be recorded (hence their spectra) and optimizing the MTF accordingly. However, psychophysical or subjective factors also influence the result; in general we do not know what kinds of reproduction are best for use by human observers.

The nature of the problem can be illustrated by a concrete case. In Figure 6.F.3 the MTF's A and B, respectively, correspond to a diffraction-limited f/11 lens and an obstructed aperture almost diffraction-limited f/6, the latter being a fairly close simulation of the MTF of a very good aerial photographic lens. Since the MTF's cross, it is not immediately obvious which will be the better. Clearly the bandpass of A is much wider, but B provides substantially higher modulation for intermediate frequencies. It is known from actual experiment that A gives better image quality in photographs of simulated low-contrast aerial scenes, using SO 243 film (SO 243 is essentially equivalent to 4404). "Better" means that smaller details of the original scene are reproduced, not merely that the contrast of somewhat larger details is better.

This result can be explained by analysis of the situation. If we draw the SO 243 threshold on the MTF diagram, the intersection with the MTF's gives the high-contrast resolving power. As would be expected, B gives better resolution than A. To find the resolving power for any other contrast,

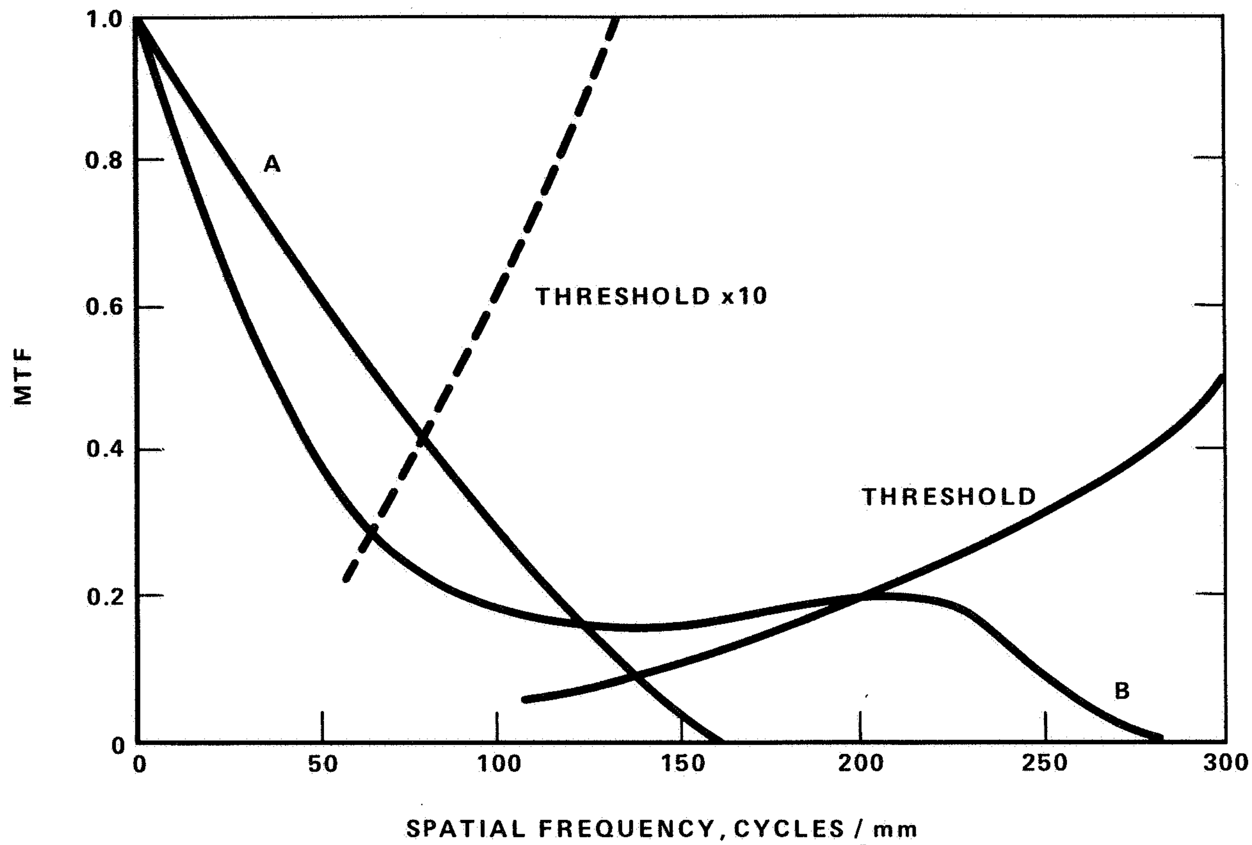

FIGURE 6.F.3

we could multiply all MTF ordinates by the desired modulation, e.g., 0.33 for 2-to-1 targets. It is more convenient in this case to perform the equivalent action of multiplying all threshold ordinates by the same factor. When this is done, e.g., for a target modulation of 0.1, lens A is seen to have better resolving power. (These resolution values were confirmed by experiment.) Since not all aerial details are periodic, a different presentation showing contrast as a function of bar width is also of interest. Figure 6.F.4 shows the bar-to-background image contrast for a target contrast of 2 to 1 as a function of bar width, calculated from the lens and film MTF's. Here bar width is shown increasing to the right, which seems more natural. Each curve is essentially a plot of the fractional area of the spectrum (sine function) for any bar width included under the MTF. Clearly the curves must converge for large bar widths, when either MTF would include the whole bar spectrum, but it is interesting that the curves do not cross, and A is always superior to B even down to a 2.5μ bar width, corresponding to the high-contrast resolving power for B.

From this kind of study it is clear that a single figure for image quality, e.g., a resolving-power figure, can be misleading. If resolving power is all that can be measured, then, for aerial photography, target contrast should be low--not greater than 2 to 1. In the context of space observation, where the interest often lies, not in relatively high-contrast details of, say, industrial or military installations, but rather in the more subtle tonal differences used in agricultural interpretation, one could argue for an even lower

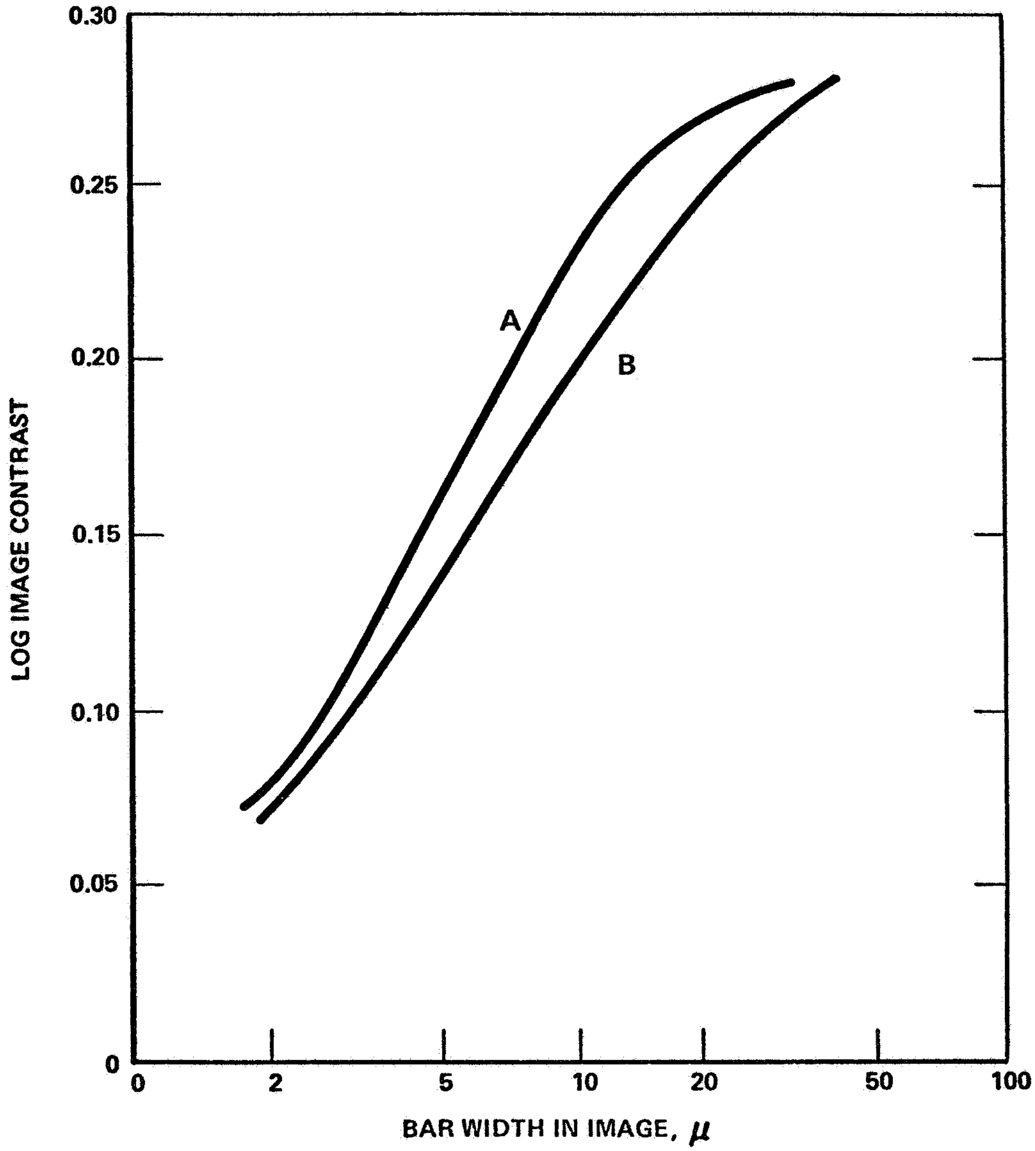

FIGURE 6.F.4

contrast, say, 1.2 to 1. However, there are technical problems in working at such low contrasts, and they are not advocated. The full picture of a system's performance cannot be had without its MTF in addition to a resolution limit.

The case here presented is that the present concentration on resolution obscures other important aspects of image quality and can lead to incorrect evaluation of systems and deductions about photointerpretation tasks. No single parameter can fully describe image quality or enable a proper comparison of one type of system with another, e.g., photo and TV, but the MTF when carefully interpreted can be the basis of a much better evaluation.

F. 6 Subjectivity and Image Shapes

Reference was earlier made to the little-known subjective factors in interpretation of photographs. Here we do not mean the special prior knowledge whereby an interpreter can deduce that a complex is an oil refinery, but rather the visual and mental process whereby the blurring of outline and distortion of shape and tone in the image of one of the pipes is accepted and discounted. This is associated with the general phenomenon that we tend to see images, not as they are, but as we would like them to be, and that our eyes are better adapted to detecting photometric differences than measuring photometric levels. We accept without thought gross distortions in the size of small images, e.g., roads in aerial photographs, if we have no reason to query them. For example, in the reproduced Gemini pictures of San Angelo, Texas, a white line representing a road is about half as wide as adjacent fields, whereas in reality it must be much narrower. As we approach the resolution limit, the size of images becomes more and more dependent on their intensity, while the shape loses resemblance to the true geometry. Especially in presence of haze, which affects dark tones more seriously, low-contrast details tend to disappear altogether, leaving only the lighter details in distorted form. Where light details are few, as in nonurban areas, interpretation without ground truth must be very difficult. No doubt for such reasons most of the Gemini photographs suggest an uninhabited planet.

The extent of image distortion at small sizes does not appear to have been intensively studied. Figure 6. F. 5 shows an example of an approach in which the intensity profile of a "bar on bar" image has been calculated, using Fourier transform programs and the MTF's of a typical system whose high-contrast resolution is 250 cycles per mm. The hypothetical target in this case is a bar of width W and intensity 1.0, located within a bar of width 2W and intensity 0.5. The rectangular outline represents the intensity profile in an ideal image at such a scale that $2W = 25\mu$. The curve shows the intensity profile in the calculated image; the intensity has dropped to 60%, and the base has a spread out to about twice the correct width. Clearly a resolution of 250 lines per mm (bar plus space = 4μ) conveys a false impression of quality. Figure 6. F. 5 does not include the photographic gamma, which would tend to sharpen up the edges but would introduce further distortions.

Since the eye can accept this kind of distortion without undue worry, it is clearly not possible to predict from <u>a priori</u> or purely physical considerations what kinds of image quality are "good." Until much more is known about objective-subjective relationships, competitive systems should always be finally tested under realistic, practical conditions. Much can also be done by well-conducted simulations using models.

F. 7 Conclusions

This discussion has been conducted mainly in terms of the parameters now used to evaluate photographic systems, viz., limiting resolution, MTF, granularity, and gamma. It has been shown that resolution alone is an incomplete description and can be misleading. This is not to say that resolution is useless; no other test of comparable simplicity could wrap up into

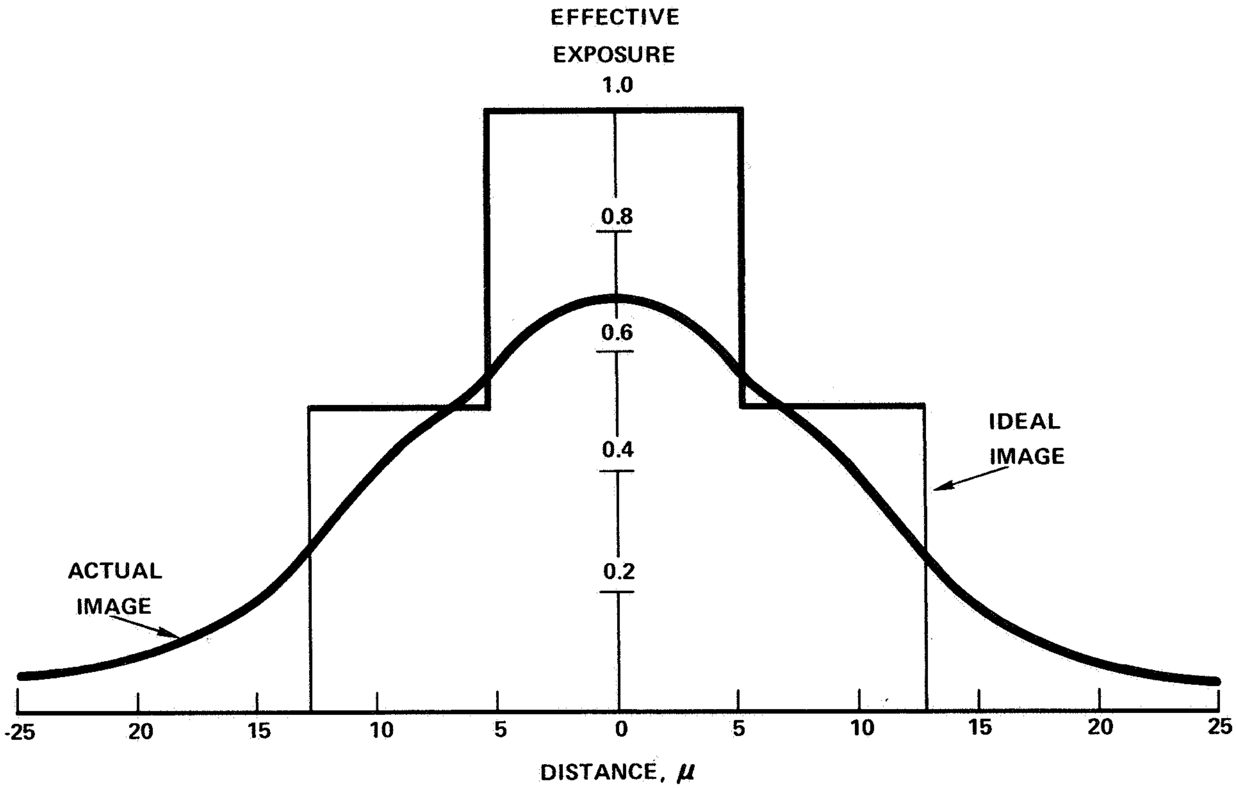

FIGURE 6.F.5

one compact summary so many factors that influence image quality, including above all the subjective factors. But resolution clearly fails when photographic systems have widely different MTF shapes and when they depart from a typical MTF and granularity balance. We may therefore argue, a fortiori, that the comparison of fundamentally different systems, such as photography and television, should take account of all parameters that can be measured, and that human observers should not be left out of the evaluation until it is too late.

Research and development are necessary to establish more clearly the fundamentals of image quality and the subjective processes whereby pictures are interpreted.

F.8 Definition of Contrast

Contrast is a familiar concept but is defined in different ways by various users. Some definitions are given here for reference.

Suppose a pattern, e.g., a three-bar target, has two levels of luminance, B_1 and B_2, corresponding to the bars and the background. The simple definition of contrast is then:

$$C = B_1 / B_2$$

Another definition, little used in photography is:

$$C = B_1 / B_1 + B_2$$

In photography a logarithmic scale is often used, because the numbers fit conveniently to H and D curves. Target contrasts are often measured and expressed directly as density differences. Thus log contrast, or log luminance ratio, is

$$\log C = \log (B_1 / B_2) \text{ or } \log B_1 - \log B_2, \text{ or density difference.}$$

More recently, use of MTF's has brought into use the expression of contrast as modulation. Thus,

$$\begin{aligned} M &= B_1 - B_2 / B_1 + B_2 \\ &= C - 1 / C + 1 \\ &= 10^D - 1 / 10^D + 1, \text{ where D is density difference.} \end{aligned}$$

Modulation numbers are approximately the same as density differences for values up to 0.7 or so. Equivalents are given in the table below.

Contrast	Density Difference	Modulation
1000:1	3.0	0.99
100:1	2.0	0.98
10:1	1.0	0.82
2:1	0.30	0.33
1.26:1	0.10	0.11

APPENDIX G

ON AUTOMATED DATA PROCESSING

S. S. Viglione

G. 1 Statistical Classification

Given a set of sample pattern vectors $\overline{X}j$ for each class, assign an unknown pattern $\overline{X}$ to a particular class. Employ the notion of a probability-density function to describe the scatter of pattern points. Assume that the patterns belonging to any class, k, are random variables governed by a probability-density function $p(\overline{X}_j/k)$.* If the probability-density function is known, then a statistical technique can be used to derive the optimum** method for assigning $\overline{X}_j$ to a particular class. To perform the classification, the quantities $p(\overline{X}_j/k)p(k)$ for $k = 1, \ldots K$ must be computed and $\overline{X}_j$ is assigned to that class k_o corresponding to the largest value of these quantities. p(k) is the a priori probability that $\overline{X}_j$ belongs to class k.

In most statistical techniques it is assumed that the scatter of patterns belonging to a particular class is Gaussian. That is, for each $k = 1, \ldots K$, $p(\overline{X}_j/k)$ is Gaussian with mean vector $\overline{\mu}_k$ and covariance matrix ξ_k. The n-dimensional Gaussian density function can be expressed as:

$$\lambda_k = p(\overline{X}_j/k) = \frac{1}{(2\pi)^{n/2}\left|\xi\right|^{1/2}} \exp\left[-1/2(\overline{X}-\overline{\mu}_k)^T \xi_k^{-1}(\overline{X}-\overline{\mu}_k)\right], \tag{1}$$

where $\overline{\mu}_k$ and ξ_k are estimated from a sample set of preclassified patterns. Taking the $\log_e$ of this function:

$$\log_e \lambda_k = -1/2\left[(\overline{X}-\overline{\mu}_k)^T \xi_k^{-1}(\overline{X}-\overline{\mu}_k) + \log_e\left|\xi_k\right| + n \log_e 2\pi\right]. \tag{2}$$

The classification problem is then computing these functions for each unknown pattern $\overline{X}_j$ and assigning it to the class, k, for which λ_k is largest. For the two-class problem the ratio of λ_1/λ_2 is computed. If the ratio is greater than one, the pattern is assigned to pattern class 1; if it is less than one, it is assigned to pattern class 2.

---

*$P(\overline{X}_j/k)$ = probability of X given class k.

**Optimum is used in the sense that the probability of classifying a pattern in error is minimized.

In log form this becomes:

$$\log_e\lambda_1 - \log_e\lambda_2 = -1/2\left[(\overline{X}-\overline{\mu}_1)^T \Sigma_1^{-1}(\overline{X}-\overline{\mu}_1) - (\overline{X}-\overline{\mu}_2)^T \Sigma_2^{-1}(\overline{X}-\overline{\mu}_2) + \log_e\left|\Sigma_1\right| - \log_e\left|\Sigma_2\right|\right]. \quad (3)$$

For positive values of this function, $\overline{X}$ is assigned to class 1; for negative values, $\overline{X}$ is assigned to class 2. The decision surface is then defined as the region where $\log_e\lambda_1 = \log_e\lambda_2$ and is, in general, a second-order (quadric) discriminant function.

Graphically this can be demonstrated as in Figure 6.G.1. Here it is assumed that the measurement space is two-dimensional, i = 2. The plots represent contours of equal probability and are elliptic for the Gaussian assumption with the major axis of the ellipse defined by the principal eigenvectors of the covariance matrixes.

In the one-dimensional case, the graphical depiction is even more readily apparent (see Figure 6.G.2). The means of the distributions are readily identified as the modes in the Gaussian case, and the variance defines the spread of the distribution. The decision surface, which is linear in this case, is a line defined by that value of x where the density functions are of equal height. (This presentation also effectively demonstrates the

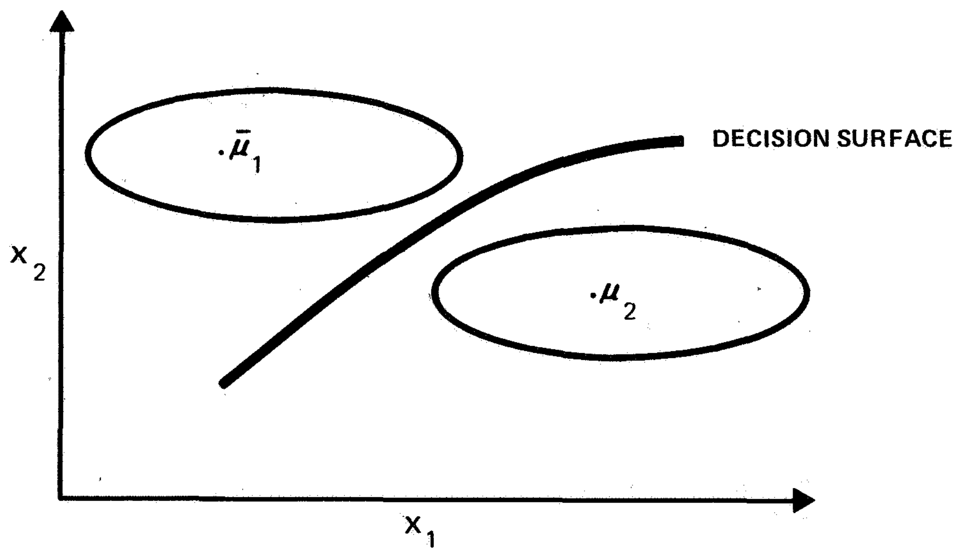

FIGURE 6.G.1

probability of error, which is less readily envisioned in the multidimensional case.)

This classification procedure can be readily mechanized in terms of a threshold logic unit (see Figure 6.G.3). The input to the unit consists of the sensory inputs, i, multiplied by an appropriate weighting function. In

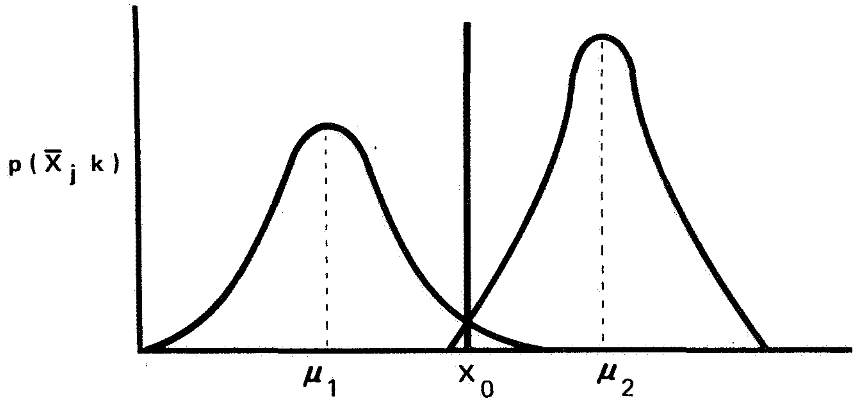

FIGURE 6.G.2

terms of the single-dimensional case, this function becomes $g(x) = x_o$ and if $g(x) > x_o$ then x is assigned to class 2. If $g(x) < x_o$ then x is assigned to class 1. For the two-dimensional case, the function to be mechanized

$$g(x) = w_2 x_1^2 + w_4 x_2^2 + w_1 x_1 + w_3 x_2 + w_5 x_{12} + d, \tag{4}$$

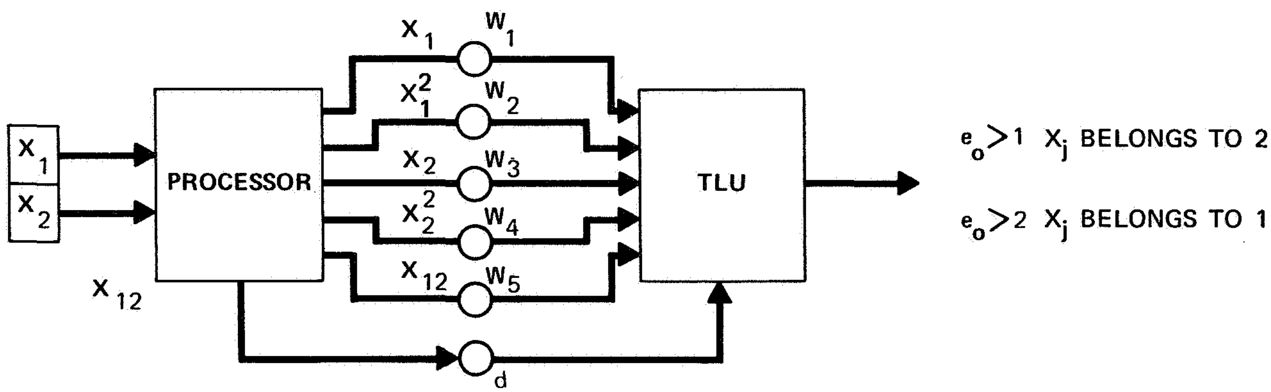

FIGURE 6.G.3

where the values of the weights are specified by the solution of Eq. (4). The threshold logic unit (TLU) merely compares the weighted sum of the input with a threshold (d) to assign a classification of the output.

G. 2 Nonparametric Classification

The foregoing discussion has been concerned with classical statistical decision theory using parametric analysis techniques. If, as is frequently the case in real-world problems, the assumption of normality is not valid, then classification based upon the knowledge of the first two moments of the distributions is not optimum. The idea of calculating a discriminant function to define the separating surface can still be applied. The derivation of the discriminant function, however, is accomplished empirically by a "training" procedure on a preclassified set of patterns.

To obtain complex decision surfaces other than linear or quadratic in the classification space, it is customary to introduce a parallel layer of multiple threshold logic units (TLU's) in conjunction with output detectors that perform a linear operation, such as majority or maximum detection, on the first-layer outputs. The system then takes the form shown in Figure 6.G.4. The first layer of units and the associated input weights are referred to as property detectors with the consideration that they detect properties, such as local modes of a multimodal distribution. The second layer is the output or response unit that correlates the resulting property profile of a pattern with a prototype of a specific pattern class. The weighted interconnections, which define the property extracted by each first-layer unit and the prototype for a pattern class, are arrived at as a result of a "learning" procedure on a set of preclassified patterns during which the weights are adjusted. The result is a nonlinear decision surface in the original signal (x_i) space consisting of pieces of a linear or a quadratic surface.

As an example, consider the two-dimensional classification task given in Figure 6.G.5. The two classes are not separable by an analysis of the first two moments of the distributions and cannot be readily distinguished by a first- or second-order decision surface. However, by generating a number of linear surfaces (shown as dashed lines) and combining them through an "and" or "or" gated output decision element, a piecewise linear surface (shown in heavy lines) is generated that uniquely separates the two pattern classes. Each linear surface is identified by a single first layer, TLU, the input weights defining the slope of the line, and the axis-crossing specified by the threshold. The weights and threshold of the second-layer unit select the appropriate line segment to form the nonlinear classification space. This procedure can be readily extended to the multidimensional, multiclass problem. The adaptive procedure is then a search for the combination of first- and second-layer units, and their associated weights and thresholds required to perform the classification task, the specification of the decision surface being accomplished by the examination of a set of training patterns.

G. 3 Preprocessing

In many cases the output of the sensors can be conditioned, transformed, or massaged in some way to ease the task of the recognition system. This signal conditioning is usually labeled preprocessing. The functions that can be performed under this heading include subsection scanning to reduce the data input, edge detection, filtering, smoothing, image enhancement, and signal correlation. These operations can be performed for the most part either optically or electronically.

Image enhancement includes operations such as averaging and noise reduction, thickening or thinning of lines, and contouring or edging. A simple technique for averaging and noise reduction is to examine a local high-intensity region (small number of resolution elements centered on a white or a black element) and to compare the average intensity with a threshold. If above the threshold, all the encountered cells are converted to

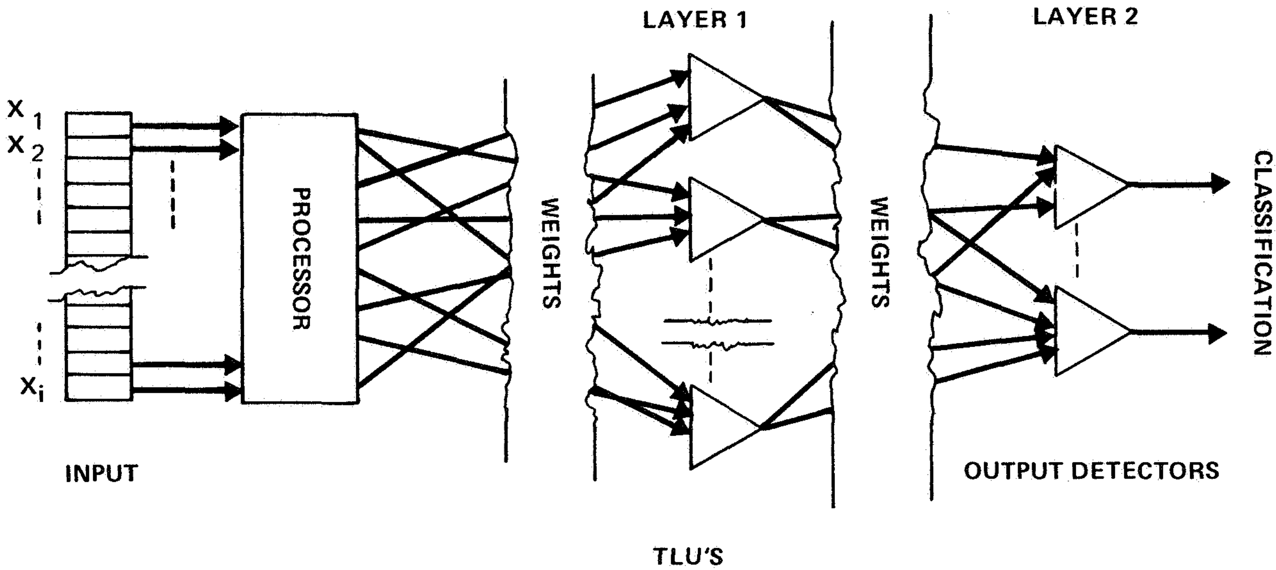

FIGURE 6.G.4

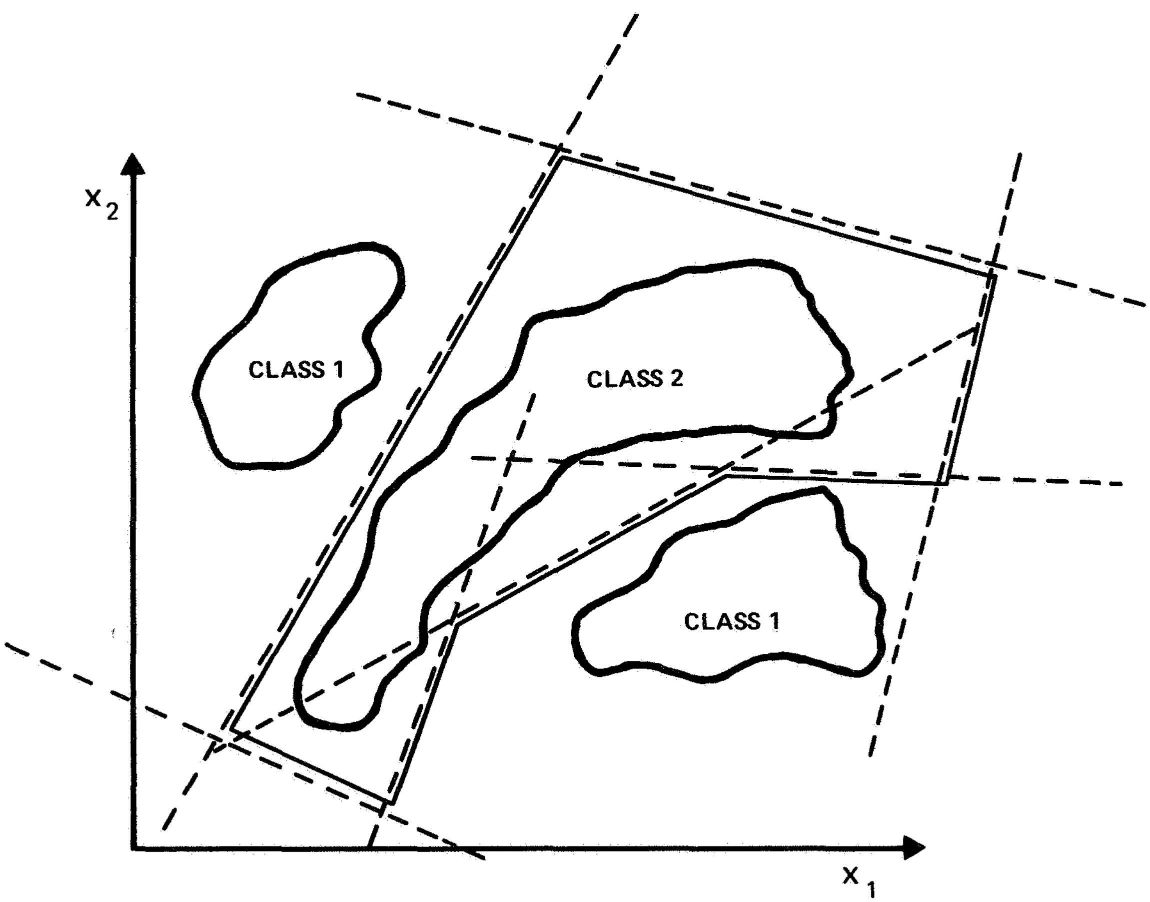

FIGURE 6.G.5

black or the gray level of the center element, and vice versa if below the threshold. The result is that solid figures are filled in and "specks" are removed. Using the above concept of a small window centered on an element of high-intensity (black cell), connected regions and edges can be highlighted in a similar fashion. For example, the adjacent elements (to the center element) are compared and, if above a threshold, they are marked for retention. The window is then centered on each of the retained elements and the process repeated across the image. When completed, each element not marked for retention is converted to white, or a gray scale less than the threshold, emphasizing the connected regions.

Some of these operations can be performed on the analog voltage output of a scanner as well. The averaging or noise reduction is accomplished in part by a low-pass filtering operation. Contrast enhancement can be accomplished by signal amplification particularly if the signal variation is riding on a large dc or slow-varying level. This dc component is removed, and the remaining signal is amplified. Thus the background is subdued and the signal content enhanced. Laplacian or gradient filtering operations are techniques for edge enhancement which have been used quite effectively. In Laplacian filtering, the analog output of the scanner is differentiated twice and averaged over the four (constant velocity) scan paths shown in Figure 6.G.6. In gradient filtering, the output of the scanner is differentiated once, squared, and then averaged over the same four scan paths. Each of these operations will enhance edges or contours and suppress regions of uniform brightness. It is conceivable that the operations suggested above can be performed on board the spacecraft prior to transmission of the data, again with the intent of ensuring high-quality data, reducing the data-

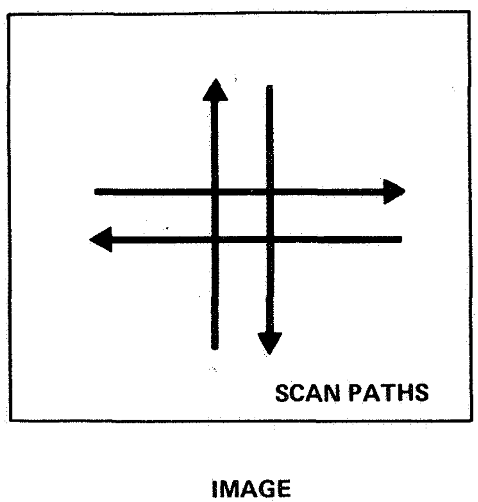

FIGURE 6.G.6

link channel requirements, and easing the ground-processing task. In addition, they can be performed at the input to the on-board processing system discussed previously to assist in the data classification.

Optical filtering and correlation have appeal due to the basic parallel nature of the processing involved. Large amounts of data (bits) can be handled simultaneously. The mathematical functions such as auto- and crosscorrelation, frequency analysis, and filtering can be performed on a spatial image at very high speeds. The resulting correlated or filtered output can be monitored by a photodetector or detector array and readily converted to an electrical signal for computer processing.

The following discussion is taken from Cutrona in Optical & Electro-Optical Information Processing, edited by Tippett et al., MIT Press, 1965.

"The mathematical operation of correlation is basically one of comparing two functions to determine the extent to which they are similar or different. In general, when two functions are crosscorrelated, the result will be a function whose peak value indicates the degree of similarity between the two functions; the position of this peak indicates the position of best correlation. The operations to be performed are given by:

$$\phi_{fg}(x_o) = \int f(x)\, g(x-x_o)\, dx \qquad \text{crosscorrelation}$$

$$\phi_{ff}(x_o) = \int f(x)\, f(x-x_o)\, dx \qquad \text{autocorrelation}$$

and can be mechanized by an optical system of the form shown in Figure 6.G.7.

"The source and collimating lens to the left of the plane P_1 cause a plane coherent wave to be incident on the transparency $f(x, y)$. The optics between planes P_1 and P_2 causes the spectrum analysis of $f(x, y)$ to appear in the plane P_2. The optics between planes P_2 and P_3 performs a second spectrum analysis of the signals in plane P_2. Thus incident upon P_3 is the function $f(x, y)$. If one looks through plane P_3 toward the source, the distribution of light will be the product $f(x, y) g(x, y)$. If the transparency containing $f(x, y)$ can be moved in the plane P_1, along the x axis, then for a displacement x_o, the distribution of light at P_3 will be the product $f(x, y) g(x - x_o, y)$. The combination of spherical and cylindrical optics between P_3 and P_4 causes a multichannel spectrum analysis of the light distribution emerging from P_3. The distribution of light in P_4 is then:

$$\phi(x_o, y; \alpha) = \int f(x, y)\, g(x-x_o, y)\, e^{i\alpha z} dx,$$

$$\alpha = \frac{\lambda \pi}{\lambda} \sin\theta.$$

$\alpha = 0$ corresponds to the light in a slit parallel to the y axis. If only the light in the slit is recorded the equation becomes:

$$\phi(x_o, y, 0) = \int f(x, y)\, g(x-x_o, y)\, dx = \phi_{fg}(x_o, y),$$

the two-dimensional crosscorrelation functions. To perform an autocorrelation, a second copy of $f(x, y)$ is used in plane P_3. The correlated output can be recorded on film or sensed by a photomultiplier or photodiode array."

In the discussion above it was noted that the frequency spectrum of $f(x, y)$ appeared at plane P_2. If the interest is in an object contained in $f(x, y)$, an examination of its frequency components might be appropriate

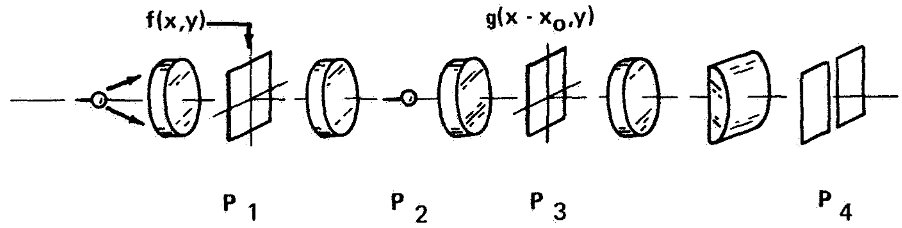

FIGURE 6.G.7 Optical correlator.

rather than a correlation with the object itself. One advantage of this is that the frequency spectrum of the object is essentially the same no matter where it is located in f(x, y); that is, the spectrum is translationally invariant (not rotationally invariant, however). Spatial filtering of the image can be performed by blocking or transmitting certain portions or bands of the spectrum. The point on the optical axis is often called the dc or zero-order component. The higher frequencies appear at corresponding distances off axis. To accomplish the filtering operation, a transparency is constructed, opaque in certain regions, and placed on axis in plane P_3. Examples of such filters are shown in Figure 6. G. 8.

The high-pass filter, for example, emphasizes the high-frequency content of f(x, y) and can be used to enhance features such as edges. The low-pass filter can be used to perform a smoothing operation or reject noise in the image.

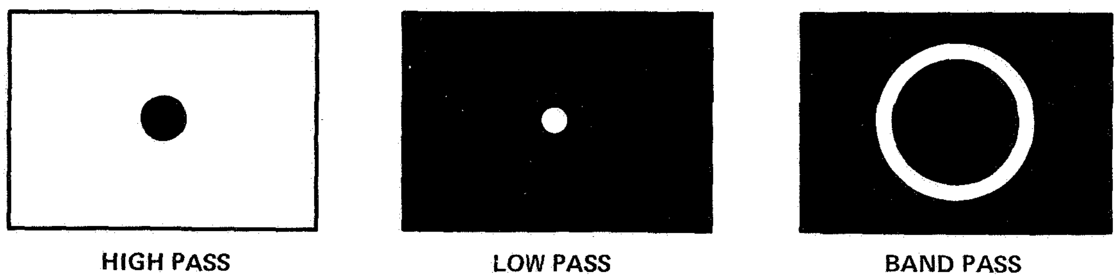

FIGURE 6. G. 8 Spatial filters.

The preceding discussion was presented only to suggest the operations that could be performed under the title of "preprocessing." The purpose of preprocessing could be to enhance the image, to ease the task of analyzing its detailed content, or to reduce the redundancy in the image for ease of subsequent transmission or data processing. Several schemes have been in use for the past few years, based upon the principles discussed in part above, for reducing the bandwidth required for picture transmission.

As a conclusion, a discussion of such a technique seems appropriate. The block diagram (Schreiber et al., 1959) shown in Figure 6.G.9 demonstrates a technique that achieves bandwidth reduction and yet is theoretically capable of reproducing the original image. It is a partial mechanization of the gradient filtering technique mentioned earlier. The video signal, derived from an image by scanning, is passed through a low-pass filter with frequency response $L(jw)$. If the bandwidth of the low-pass filter is 1/10 that of the original video signal, $s(x)$, then the output $a(x)$ can retain the original number of bits to avoid quantization noise. The video signal $s(x)$ is also passed through a differentiator. Since ds/dx is large at the edges, this signal contains mostly edge information. If both $a(x)$ and ds/dx are transmitted exactly (through a noiseless channel) then the high-frequency part of $s(x)$ can be synthesized by passing it through a generator with a frequency response of

$$H(jw) = \frac{1-L(jw)}{jw}.$$

The output of $H(jw)$ will be

$$b(x) = s(x) - a(x)$$

and the sum of $a(x)$ and $b(x)$ is exactly $s(x)$.

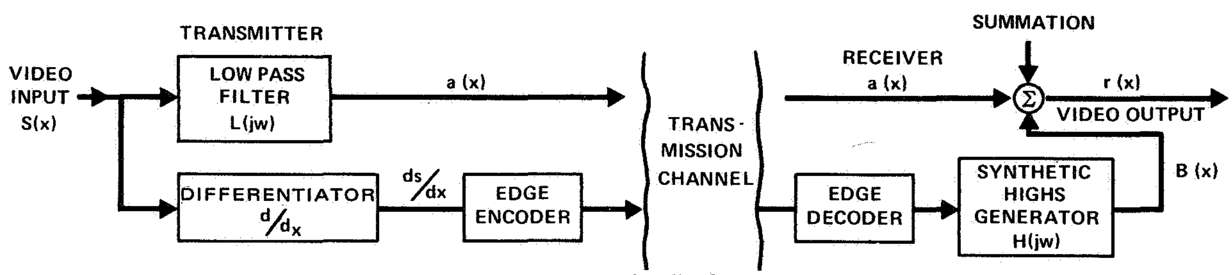

FIGURE 6.G.9

In Schreiber's system, ds/dx was quantized to 3 bits. Only the magnitude and level of edge points (level changes) were transmitted—achieving overall reduction in bandwidth of 4:1.

An extension of the above to two dimensions was suggested by Schreiber in 1963. As shown in Figure 6.G.10, the differentiator is replaced by a gradient operator. A pair of two-dimensional filters, H_1 and H_2, are required to synthesize the high-frequency part of $s(x, y)$. If, as above, the low-frequency component, $a(x, y)$, and the gradient components, ds/dx, ds/dy, are sent exactly, then the high-frequency component can be synthesized [i.e., $s(x, y) - a(x, y)$] exactly by using appropriate $H_1(ju, jv)$ and $H_2(ju, jv)$ and the original picture reproduced. Bandwidth reduction of 10:1 to 20:1 is postulated with this technique.

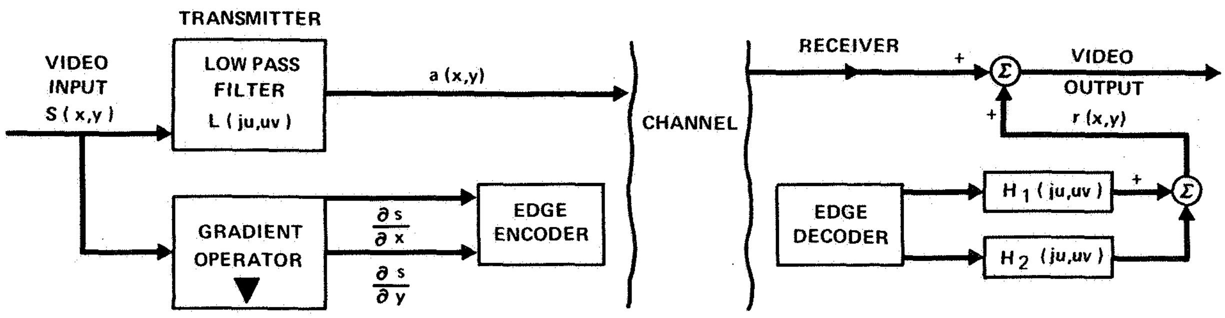
TRANSMITTER
VIDEO
INPUT
S (x,y)
LOW PASS
FILTER
L (ju,uv)
a (x,y)
GRADIENT
OPERATOR
▼
∂s/∂x
∂s/∂y
EDGE
ENCODER
CHANNEL
RECEIVER
+
Σ
VIDEO
OUTPUT
r (x,y)
+
EDGE
DECODER
H 1 (ju,uv)
H 2 (ju,uv)
+
Σ

FIGURE 6.G.10

APPENDIX H

COMMENTS ON APPENDIX E "COMMENTS ON AIRCRAFT AND SPACE SURVEY SYSTEMS"

Prepared by Brian O'Brien
for the Central Review Committee

The satellite example cited in Appendix E by Amrom H. Katz assumes direct photography with physical recovery of film. This leads to an assumed satellite life of two weeks with corresponding high cost.

The Committee notes that television state of the art permits 200-foot resolution in a black-and-white picture 100 miles on a side. This resolution is not yet available in color because of registration problems, but it is estimated that these problems can be solved and that color television of the above quality will be available within three years.

The result of using television in place of direct photography is to extend satellite life to a year or more, and to permit the repetitive coverage required by the forestry-agriculture-geography groups. This change can reduce costs by more than an order of magnitude below those estimated for direct photography.

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Supported by private and public contributions, grants, and contracts, and voluntary contributions of time and effort by several thousand of the nation's leading scientists and engineers, the Academies and their Research Council thus work to serve the national interest, to foster the sound development of science and engineering, and to promote their effective application for the benefit of society.

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